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Spectrum and magnetic variations of the remarkable helium-strong star HD 37776
I. Observations and data reduction

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Abstract. HD 37776 is a magnetic He-strong star which displays a very strong, clearly nondipolar magnetic field. If this field is dominantly quadrupolar, HD 37776 may have the strongest photospheric magnetic field ever detected in a nondegenerate star. In order to study the structure of the magnetic field of this object, we have undertaken a study of line profile structure and variability in circular polarization spectrum. More than 60 new Zeeman spectra of HD 37776 have been obtained, well distributed throughout the rotational phase. These spectra were acquired using the 6 m telescope and the Main Stellar Spectrograph (MSS) with Zeeman analyzer. A brief description of the observing technique is presented, and the data reduction technique is summarized. Investigations of the positional and photometric accuracy of the spectropolarization measurements have been made, and systematic errors have been studied. The spectral and magnetic variations of HeI λ 5875.7 and SiIII λ 4552.6, λ 4567.9, λ 4574.8 were investigated. The equivalent width of λ 5875.7 line shows a double-wave variation, in excellent agreement with previous investigations. Variation of the equivalent width of SiIII lines is not in contradiction with previous observations. Our data comprise strong evidence for the important role of the magnetic field in formation of this line. Measurements of centres of gravity and core positions of HeI λ 5875.7 in orthogonal polarizations provide additional evidence for the existence of a very strong photospheric magnetic field with a highly complex structure.

Key words: stars: helium-strong stars: individual: HD 37776 – stars: magnetic fields

1. Introduction

Driven by the detection of strong magnetic fields in sunspots by Hale in 1908, a succession of attempts to detect magnetic fields in stars led to the success of Babcock in 1947, who found a line-of-sight magnetic field component of 2 kG strength in the Ap star 78 Vir. Babcock had constructed a special differential circular polarization analyzer for simultaneous measurement of the orthogonally polarized spectra. The shifts of lines between such spectra are proportional to the line-of-sight (or longitudinal) component of the star's magnetic field.

From 1947 to 1958 Babcock detected strong, ordered magnetic fields in 89 stars (Babcock, 1958). Unfortunately, Babcock's technique is effective only for stars with very simple magnetic field structure, with mainly the same sign of the local longitudinal field component over the whole visible stellar hemisphere. In the case of a complex field (for example, the magnetic field of the Sun) no net shift is detectable between lines in orthogonally circular polarized spectra, even in the presence of a very strong (several kG) field.

Continuing his circular polarization measurements, Babcock (1960) discovered Zeeman splitting of lines in the unpolarized spectrum of the Ap star HD 215441. Magnetic splitting of lines in unpolarized spectra constrains a mean magnetic field modulus over the visible stellar hemisphere. For HD 215441, Babcock inferred a mean magnetic field modulus of 34 kG, which remains to this day the strongest magnetic field detected in a nondegenerate star. Indeed, while magnetic fields of similar strength have been detected in a handful of other CP stars (HR 7129 with a mean field of 28 kG (Wolff and Wolff, 1976)), these appear to be exceptional objects, with the average field strength among magnetic CP stars being below 1 kG.

In the 1970s, megagauss dipolar magnetic fields were discovered in magnetic white dwarfs (Angel and Landstreet, 1970). As new digital devices were developed in the 1980s, investigators were able to begin to probe the fine structure of line profiles, and to search for magnetic fields with considerably more complex structures, particularly in cool stars (Robinson, 1980). The methods used to detect such complex stellar magnetic field in cool stars differ considerably from Babcock's line shift technique. Measurements of magnetic fields in cool stars show that their strengths are never larger than a few kG, with surface filling factors of the order of 10% (whereas filling factors for magnetic CP stars appear to be very close or perhaps identically equal to 100%).

In the last decade, important evidence of existence of stronger magnetic fields in CP stars has been obtained. Due to a persistent search by Canadian and Russian astrophysicists, the magnetic He-strong star HD 37776 has been discovered.

HD 37776 is the central star of the nebula IC 432, a member of the I Ori O-association (Johnson, 1955). The distance to the nebula is about 500 pc. Crawford (1958) performed two-dimensional classification of HD 37776 and determined a spectral class of B2 V. Crawford and Barnes (1966) found a distance modulus $m - M = 9.6$ and showed that HD 37776 and IC 432 are located at a greater distance than the other stars in the Orion belt. Van den Berg (1966) noted that the structure of IC 432 differs significantly in the plates obtained through red and blue filters. McNamara and Larsson (1962) determined a projected rotational velocity of 145 km/s for HD 37776.

During the investigation of young stars in Orion, Nissen (1976) discovered that HD 37776 has stronger than normal helium lines. Pedersen and Thompsen (1977) obtained photoelectric observations in HeI λ 4026 line and discovered variability with a period of 1.5385 days. Later, Pedersen (1979) determined that the helium variations and *uvby* photometric variations occurred in phase, and with the same period. In addition, Walborn (1982) noted that SiIII lines vary in antiphase with HeI.

The magnetic field of HD 37776 was discovered by Borra and Landstreet (1979) using measurements of circular polarization in the wings of H_β. Later, Thompson and Landstreet (1985) found that, when phased according to the ephemeris JD 2445724.669 + 1.53869 E, the longitudinal magnetic field displays a double-wave variation, with extrema of −2 kG and +2 kG. They concluded that the magnetic field geometry differed significantly from a simple dipolar configuration, as had been observed for many other magnetic A and B stars. Bohlender (1988) and Bohlender and Landstreet (1990) proposed a complex multipolar (dipole+quadrupole+octupole) magnetic field model, which reproduced the longitudinal field variation of HD 37776 quite well. This model predicts a 60 kG mean field modulus, considerably in excess of that observed for HD 215441 (Fig. 1).

A few years later, Kopylova and Romanyuk (1992), using photographic Zeeman spectra of HD 37776, noted that some lines (SiIII, MgII, CII) have very different profiles in orthogonally circular-polarized spectra; broadening and even splitting were seen. Were this broadening magnetic in origin, a 70–80 kG magnetic field would be required. Unfortunately, the accuracy of these photographic measurements was low, and accurate profile measurements were impossible.

An attempt to measure continuum circular and linear polarization of HD 37776 (Romanyuk et al., 1992) was also made. Measurements were obtained using the hydrogen-line magnetometer of the 6 m telescope. Romanyuk et al. (1992) detected constant, nonzero linear polarization and zero circular polarization in the continuum, and concluded that the linear polarization was circumstellar or interstellar in nature.

Bohlender (1994), using Balmer-line longitudinal field measurements and high S/N unpolarized spectra, published a multipolar magnetic field model: a coaxial dipole, quadrupole and octupole, with polar field strengths of +3.4 kG (dipole), −59 kG (quadrupole), and +44 kG (octupole). While this magnetic field geometry reproduces the longitudinal magnetic field measurements and unpolarized line profile variation quite well, further observations are necessary in order to determine whether the proposed field geometry is indeed a good representation of the magnetic field of HD 37776.

Recently Adelman (1997) made Stromgren *uvby* observations of HD 37776. He improved the period of photometric variations. He adopted the zero phase of Thompson and Landstreet (1985) and found:

$$JD = 2445724.669(\pm 0.02) + 1.538675(\pm 0.000005)E.$$

HD 37776 has a single maximum in *uvby* which occurs at approximately the same time in each colour near phase 0.75 with an amplitude of $0^m_.03 - 0^m_.04$.

Further progress can be obtained from detailed analysis of high S/N Zeeman spectra of this star. Since the appearance of a new CCD detector on the MSS of the 6 m telescope, we have been obtaining such observations using the Zeeman analyzer.

2. Observations

2.1. Observing technique

Our observations of HD 37776 were obtained from October 1994 to September 1997 with the MSS of the 6 m telescope, in the red and blue spectral ranges.

More than 60 Zeeman spectra have been acquired, well distributed over the rotational period of the star.

The MSS was used in these measurements primarily due to our experience with this instrument, hav-

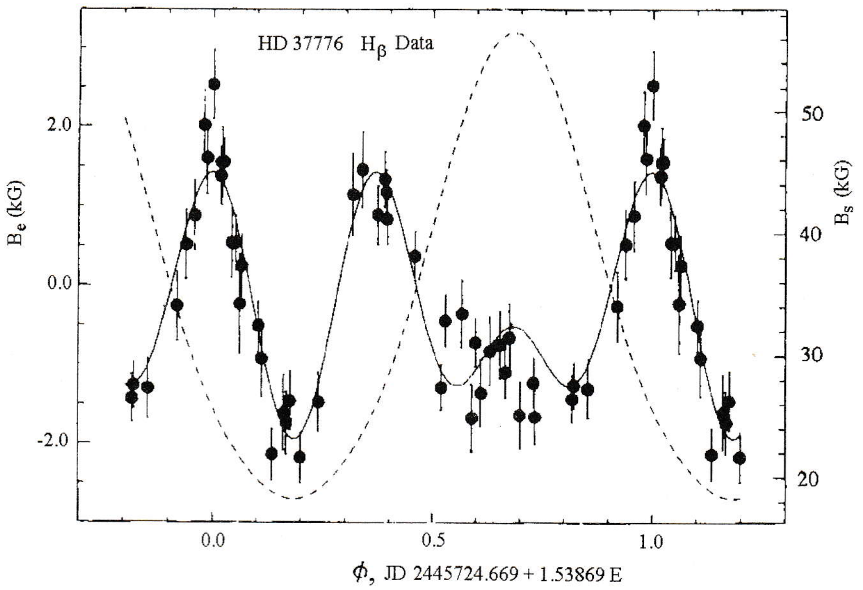

Figure 1: *The longitudinal field of HD 37776 and model field variations (Bohlender, 1988). The solid curve is the longitudinal field variation produced by the model and the dashed curve is the mean field modulus variation produced by the model.*

ing obtained over 2000 spectra using the Zeeman analyzer. In addition, there is forcible evidence that magnetic measurements obtained with this instrument are in good agreement with those obtained at other observatories (Wade et al., 1997).

The first Zeeman observations with the CCD showed immediately that the magnetic field of HD 37776 must be very strong. A brief description of results of these measurements was published in two short papers (Romanyuk et al., 1995, 1997). The principal goals of the present paper are to disseminate the observations to date, to describe our observing technique, and to present our measurements of the spectral and magnetic variability of HD 37776.

Observations were carried out with the achromatic circular polarization analyzer (Najdenov and Chountonov, 1976). The devices and technique of photographic Zeeman measurements have been described several times in the literature (e.g. Bychkov et al., 1988). In this investigation we have employed 2 different CCD detectors, controlled using DOS and UNIX operating systems. Since we have no description of our Zeeman measurement techniques with the CCD yet, we describe them here.

From October 1994 to 1996 we used the red CCD detector (K 585 format 530 × 580 px (Borisenko et al., 1991)). This CCD was mounted on the MSS by V.E. Panchuk and his colleagues. The pixel size is 18 × 24 μm, and the effective spectral range is 5000–7000 Å. This detector is controlled under DOS. Observations of HD 37776 employed the second camera of the MSS (D = 14 Å/mm, spectral resolution 0.25 Å/px). An analysis of emission-line comparison spectra shows that in all cases a nominal instrumental profile image of 2.0–2.5 px has been obtained. We have reduced our spectra in a standard way with cosmic rays removed, wavelength calibration and continuum determination. The comparison source was a ThAr emission lamp, with the line identification made using the atlases of Burenkov et al. (1979) and D'Odoriko et al. (1984).

Data reduction was performed using the reduction packages DECH and DECH–20 (Galazutdinov, 1992). The work with one-dimensional Zeeman spectra included determination of the centres of gravity of spectral lines using codes of V. V. Vlasyuk (VECVIZ) and G. A. Galazutdinov (DECH-20). The longitudinal component of the magnetic field was determined in the same manner as the earlier analysis of photographic data: a value proportional to the relative shift of the centres of gravity of spectral lines measured in the two orthogonally circular-polarized spectra.

The translation to wavelengths was done using a dispersion solution constructed by fitting the position of the comparison spectrum emission lines using a 3rd-degree polynomial fit. The continuum level was determined by fitting a spline to the "reference points", well determined places in continuum, where lines are absent.

After March 1996, we used a new 1160 × 1040 px

CCD (Chountonov and Glagolevskij, 1997); pixel size of 16 × 16 μm, working spectral range 4000–7000 Å. This device is controlled in a UNIX environment and has been installed by G. A. Chountonov expressly for magnetic measurements. The nominal (2 pixel FWHM) spectral resolution of this configuration (1160 × 1040 CCD, MSS second camera) is 0.5 Å in the 5000–7000 Å spectral range (D = 14 Å/mm) and 0.35 Å in the 4000–5000 Å spectral range (D = 9 Å/mm). Observations obtained with the 1160 × 1040 CCD detector were reduced using ESO MIDAS, and the NICE software package (Knyazev and Shergin, 1995). In MIDAS, the LONG context was used, as well as some MIDAS codes authored by V.S. Shergin and D.O. Kudryavtsev.

During installation, the CCD detector was oriented in such a way that the axis of the CCD was parallel to the dispersion direction. For technical reasons, it was necessary to remove the CCD from the camera at the end of each observing session. It was therefore necessary to re-install the CCD preceding each observing session, requiring re-calibration of instrumental parameters. Therefore the alignment of the CCD in the imaging plane and with respect to the dispersion direction and the instrument focus differed slightly during each observing session.

It is very important to ensure high relative positional accuracy in magnetic field measurements, and it is therefore important to check the detector inclination parameters for constancy. This was done using measurements of the comparison spectra and standard (zero field) stars with narrow lines. Because of small differences in the spectrograph imaging geometry from stars and from the comparison lamp, small systematical differences in the instrumental shift from stars and from the lamp are observed.

2.2. Selection of spectral range

In the red, we had the possibility of using a spectral band 130 Å for the 530 × 580 CCD, and 220 Å for the 1040 × 1160 CCD. In the blue, we were limited to using the 1040 × 1160 CCD, with which we could obtain a 140 Å spectral band. Thus we had to select the best spectral bands for observation. As a result, we selected 3 spectral bands:

1. $\lambda\lambda$ 5820–5950 (contains the stellar lines HeI λ 5875.7, FeIII λ 5833.6 and the sharp interstellar, rather than circumstellar, lines NaI λ 5890 and λ 5896). The existence of the nonstellar NaI lines in this band is very useful as it is possible to use these lines as standards both for measurements of line equivalent widths and magnetic fields (Fig. 2).

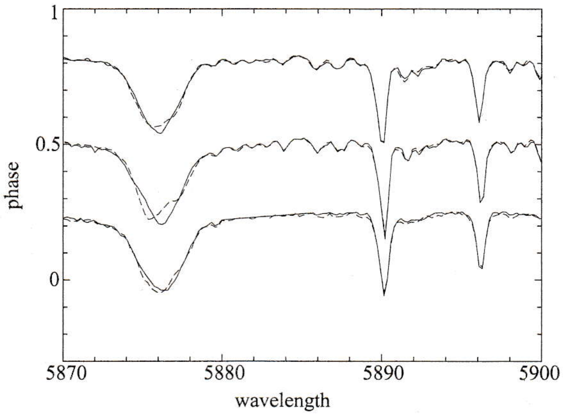

Figure 2: *Variation of HeI λ 5875.7 line profiles at three different period phases, dashed line – left circularly polarized, solid line – right circularly polarized. NaI 5890 and 5896 lines are non-polarized and non-variable.*

2. $\lambda\lambda$ 6520–6650 (contains H_α and the weak CII λ 6578, λ 6583 doublet). We (Romanyuk et al., 1995) confirmed the existence of weak emission in the core of H_α, discovered earlier by Walborn (1982). The emission is longer than the spectrum spreading beyond the boundaries. The emission source is the HII region which appears to surround HD 37776, this envelope is also, in all probability, a source of strong linear polarization.

3. $\lambda\lambda$ 4460–4600 (contains HeI λ 4471, MgII λ 4481 and SiIII triplet λ 4552, λ 4567 and λ 4574 lines). Only 7 spectra have been acquired in this region with the 1040 × 1160 CCD. The lines in this SiIII triplet have very different Lande factors (z = 1.25 for 4552 Å, z = 1.75 for 4567 Å and z = 2.00 for 4574 Å) and turn out to be very useful in construction of the magnetic field geometry.

2.3. The observed spectra

From initial examination of the HD 37776 spectra it was noted that the magnetic field of this star must be quite strong and complex, due to the obvious differences in shape of lines obtained in orthogonal polarizations. There is no simple shift as the one observed in the case of HD 215441. The log of observations of HD 37776 is presented in Table 1. Phases have been computed according to the ephemeris of Adelman (1997) (JD = 2445724.669 + 1.538675 E). The strongest lines in our selected spectral ranges are H_α, with weak emission in the core, HeI λ 5875.7, FeIII λ 5833, CII λ 6578, λ 6583, SiIII λ 4552, λ 4567, λ 4574, MgII λ 4481, and HeI λ 4471.

It is clear from Table 1 that most of our observations have been obtained in the spectral range containing HeI λ 5875.7 (about 40 Zeeman spectra well distributed over the rotational phase). Our investigation of the magnetic and spectral variations is based primarily on the study of these spectra.

Table 1: *The log of HD 37776 observations*

JD 2400000+	Phase	Spectral range (Å)	JD 2400000+	Phase	Spectral range (Å)
CCD 530 × 580			50062.392	0.129	5820–5= 950
49641.379	0.508	6520–6650	50062.416	0.144	5820–5950
49641.404	0.524	6280–6410	50087.371	0.362	5820–5950
49641.433	0.543	6190–6320	50087.396	0.379	5820–5950
49641.471	0.568	5820–5950	50088.271	0.948	5820–5950
49641.600	0.652	5820–5950	50090.338	0.291	5820–5950
49642.421	0.186	6520–6650	50090.358	0.304	5820–5950
49642.446	0.201	6280–6410	50091.242	0.879	6520–6650
49642.471	0.218	5820–5950	50091.267	0.895	6520–6650
49736.245	0.163	6520–6650	50118.179	0.385	5820–5950
49736.275	0.182	6520–6650	50118.195	0.396	5820–5950
49736.304	0.201	5820–5950	50119.166	0.026	5820–5950
49736.325	0.215	5820–5950	50119.187	0.040	5820–5950
49736.446	0.293	5820–5950	50119.425	0.195	5820–5950
49738.216	0.444	6520–6650	50121.275	0.397	5820–5950
49738.237	0.458	6520–6650	50121.296	0.411	5820–5950
49738.262	0.473	5820–5950			
49738.296	0.496	5820–5950	CCD 1040 × 1160		
49788.183	0.917	5820–5950	50413.404	0.235	5740–5960
49788.208	0.933	5820–5950	50413.442	0.280	5740–5960
49788.225	0.945	6520–6650	50414.329	0.856	5740–5960
50056.521	0.313	5820–5950	50414.353	0.872	5740–5960
50056.542	0.327	5820–5950	50415.371	0.534	5740–5960
50057.288	0.812	5820–5950	50415.396	0.550	5740–5960
50057.308	0.825	5820–5950	50415.414	0.563	5740–5960
50057.488	0.942	5820–5950	50417.487	0.909	4460–4600
50057.508	0.955	5820–5950	50417.513	0.926	4460–4600
50059.388	0.176	5820–5950	50500.251	0.698	4460–4600
50059.408	0.189	5820–5950	50681.558	0.531	4460–4600
50060.312	0.777	5820–5950	50707.471	0.372	4460–4600
50060.325	0.785	5820–5950	50709.550	0.723	4460–4600
50060.525	0.915	5820–5950	50710.492	0.335	4460–4600
50060.546	0.929	5820–5950			

3. Spectral variations

Bohlender (1988) found an extraordinary spectrum variability of HD 37776. Following Bohlender (1988), "The helium line profile variations support the idea of a band of enhanced helium which crosses the line of sight at $\phi = 0.00$ and $\phi = 0.33$ near two positive extrema of the magnetic field. Variations of profiles of silicon as well as magnesium, nitrogen, oxygen, carbon and aluminium are all similar, and indicate the presence of at least two regions of local enrichment of each element. Silicon and these other elements seem to be concentrated at the negative extrema of the effective field of HD 37776". We investigated the spectrum variations of helium, iron and silicon lines using the polarized spectra and compared our data with Bohlender's measurements. Because of the very srtrong and complex magnetic field in this star, the influence of magnetic intensification can be important.

3.1. Spectrophotometry accuracy

For detailed examination of the accuracy of our measurements we have used non-variable spectral lines.

The effective temperature of HD 37776, T_e, is 23000 K (Glagolevskij and Chunakova, 1986), therefore sharp and narrow lines of NaI λ 5890, λ 5896 cannot belong to the star. They are formed in the circumstellar envelope, must be constant and can be used for checking the accuracy of measurements.

The line identification was done using Moore tables (Moore, 1945) and VALD calculations (Piskunov et al., 1995). Equivalent widths of lines were measured using the standard procedures of DECH–20 (Galazutdinov, 1992) and MIDAS packages.

We need to check the agreement between different systems of equivalent widths because it is necessary to take into account the fact that our observations were made using different CCD detectors, and the data reduction was performed using different packages.

At first we measured the equivalent widths of the circumstellar NaI lines. We selected 2 nonvariable interstellar or circumstellar (nonstellar) NaI lines λ 5890 λ 5896 as a standard of equivalent width, W_λ. Thus we have obtained a reliable comparison of our data. Let us consider this problem in more detail.

The results of equivalent width measurements of NaI lines in two opposite polarizations are presented in Table 2. L and R are LCP (left circularly-polarized) and RCP (right circularly-polarized) profiles.

Find the average equivalent widths, W_λ (Å), obtained with two different detectors.

1) The CCD 530 × 580 detector

$$5890L = 0.226 \pm 0.023;\ 5890R = 0.225 \pm 0.021,$$
$$5896L = 0.149 \pm 0.016;\ 5896R = 0.149 \pm 0.011,$$

if we exclude measurements with *:

$$5890L = 0.232 \pm 0.019;\ 5890R = 0.231 \pm 0.016,$$
$$5896L = 0.151 \pm 0.016;\ 5896R = 0.151 \pm 0.011.$$

2) The CCD 1040 × 1160 detector

$$5890L = 0.252 \pm 0.013;\ 5890R = 0.246 \pm 0.009,$$
$$5896L = 0.153 \pm 0.006;\ 5896R = 0.151 \pm 0.005.$$

We can see that the errors in the case of the λ 5896 line are smaller than those for λ 5890. For explanation of such an effect we need first to exclude the possible influence of blends.

Using VALD (Piskunov et al., 1995), we calculated the synthetic spectra in the spectral range around the NaI λ 5890 line and λ 5896 for a nonrotating normal star with $T_e = 23000$ K and $\log g = 4.0$.

The results of VALD calculation with different carbon abundances are given in the table below. The spectral range $\lambda\lambda$ 5889–5891 was used. 3 lines with intensity > 0.01 were selected only:

Ion	λ	Line depth: Normal abund. of CII	Line depth: Underabund. of CII (0.1 dex)
CII	5889.2800	0.112	0.025
CII	5889.7760	0.267	0.124
NaI	5889.9510	0.020	0.020

Note that calculations were made for a non-rotating star, while for the fast rotating star HD 37776 the lines are essentially broader and weaker.

Thus we can see that the violet wing of the circumstellar NaI λ 5890 line is blended by the lines of CII. Usually carbon is deficient in CP stars and therefore the CII blend cannot be very strong. Nevertheless, real influence of variable carbon blending is possible.

We made the same calculations using VALD for the next spectral range, 5895–5897 ÅÅ. The VALD calculations showed only one line with a depth larger than 0.01 (in addition to the main NaI line λ 5895.992):

Ion	λ	Line depth
NaI	5895.9240	0.011

We conclude that there is no essential blending of the NaI λ 5895.992 line.

Thus, comparing the scattering of W_λ measurements from λ5890 and λ5896 we see that a probable error in σ for the NaI λ5890 line is about 20 mÅ, the λ 5896 line is not blended and its σ is 10 mÅ. Some differences in average values are not essential.

A conclusion can be drawn that the larger scattering in equivalent widths of the NaI λ 5890 line is caused by the effect of variable blending of the weak stellar CII line. The NaI lines are really interstellar or circumstellar and there is no evidence for their variations.

It is clearly seen from Table 2 that systematic differences in the measurements with different CCD detectors using different packages for data reduction do not exist!

3.2. Variation of the profile and equivalent width of the helium line 5875.7 Å

As Bohlender (1988) noted in his thesis, He has a nonuniform distribution over the surface of HD 37776, forming a belt with a maximum density near phase 0.175.

The nonuniform distribution of elements over the surfaces of magnetic stars is not extraordinary, but some very great overabundances (4–5 orders for RE-elements, for example) could probably be smaller, allowing for magnetic intensification of lines. However for this mechanism of line broadening to effectively operate great fields (tens of kilogauss) are needed.

In the case of HD 37776 the magnetic field is very strong and therefore the effect of magnetic intensification of lines must be pronounced.

As it has been mentioned above, the HeI λ 5875.7 line is not single but consists of 8 components. The VALD calculations (normal helium abundance, nonrotating star) of these for the spectral range 5874–5877 ÅÅ with lines deeper than 0.01 are as follows:

Ion	λ	line depth
HeI	5875.5990	0.265
HeI	5875.6140	0.386
HeI	5875.5990	0.265
HeI	5875.6140	0.386
HeI	5875.6150	0.436
HeI	5875.6250	0.386
HeI	5875.6400	0.420
HeI	5875.9660	0.396
FeIII	5876.3370	0.126

It can be seen that we cannot measure each HeI line separately, a blend of 8 lines forms our measured profile. The table above is presented only for illustra-

Table 2: *Equivalent widths of circumstellar NaI λλ 5890–5896*

		Equivalent widths (Å)			
JD 2400000+	Phase	5890L	5890R	5896L	5896R
		CCD 530 × 580			
49641.471	0.568	0.255	0.223	0.144	0.134
49641.600	0.652	0.244	0.240	0.173	0.157
49642.471	0.218	0.258	0.254	0.154	0.179
49738.262	0.473	0.212	0.205	0.136	0.146
49788.183	0.917	0.272	0.213	0.173	0.158
50056.521	0.313	0.213	0.239	0.138	0.143
50056.542	0.327	0.241	0.260	0.132	0.147
50057.288	0.812	0.253	0.222	0.171	0.145
50057.308	0.825	0.226	0.231	0.141	0.146
50057.488	0.942	0.215	0.230	0.130	0.138
50057.508	0.955	0.227	0.218	0.143	0.137
50059.388	0.176	0.230	0.205	0.150	0.145
50059.408	0.189	0.196 *	0.212	0.137	0.140
50060.312	0.777	0.232	0.240	0.147	0.158
50060.525	0.915	0.214	0.222	0.151	0.163
50060.546	0.929	0.221	0.220	0.150	0.159
50087.371	0.362	0.227	0.237	0.147	0.162
50087.396	0.379	0.193 *	0.233	0.151	0.150
50088.271	0.948	0.236	0.241	0.159	0.146
50090.338	0.291	0.261	0.252	0.195	0.161
50090.358	0.304	0.220	0.244	0.160	0.154
50118.179	0.385	0.185 *	0.184	0.143	0.134
50118.195	0.396	0.196 *	0.177	0.130	0.136
50119.166	0.026	0.202	0.206	0.148	0.138
50119.187	0.040	0.221	0.241	0.134	0.145
		CCD 1040 × 1160			
50413.404	0.235	0.241	0.228	0.150	0.141
50413.442	0.280	0.235	0.240	0.147	0.153
50414.329	0.856	0.258	0.254	0.155	0.156
50414.353	0.872	0.274	0.252	0.165	0.151
50415.371	0.534	0.255	0.250	0.157	0.153
50415.396	0.550	0.249	0.254	0.150	0.153
50415.417	0.563	0.251	0.245	0.152	0.149

* — lines when bad pixels or columns of CCD have influence.

tion, rotation and helium overabundances have not been taken into account.

In Table 3 measurements of equivalent width of HeI line are presented. LCP and RCP are left and right circularly-polarized profiles. Using the data from Table 3 we construct Fig. 3. From this figure it can be seen that the equivalent widths of the HeI line show a double-wave variation which is in excellent agreement with Pedersen and Thompsen's (1977) data on the R–index and Bohlender's (1988) measurements of the HeI λ 4471 line. It is interesting that the equivalent width of the $\lambda\,5875.7$ line varies in antiphase with the surface field strength in Bohlender's (1988) model.

Analyses of Table 3 and Fig. 3 show that good agreement between variations of equivalent widths of left and right polarized profiles is observed; they vary in phase and have the same amplitudes of vari-

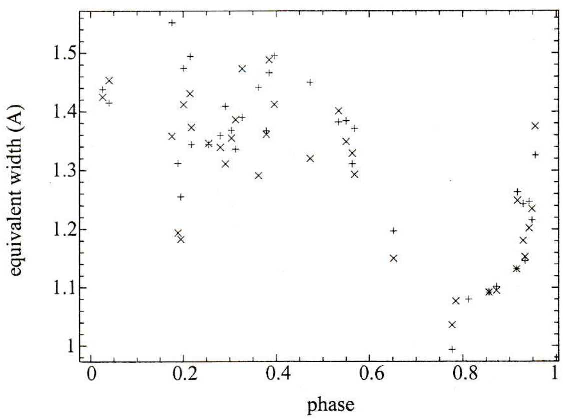

Figure 3: *Equivalent width variations of the HeI λ5875.7 line. (+ – LCP profile,* x *– RCP profile,* $\sigma = 20 - 30$ *mÅ).*

Table 3: *Equivalent width measurements of the HeI λ5875.7 line (Å)*

JD 2400000+	phase	LCP	RCP	JD 2400000+	phase	LCP	RCP
49641.471	0.568	1.371	1.293	50060.546	0.929	1.243	1.181
49641.600	0.652	1.197	1.150	50087.371	0.362	1.441	1.291
49642.471	0.218	1.344	1.373	50087.396	0.379	1.367	1.361
49736.304	0.201	1.474	1.412	50088.271	0.948	1.216	1.235
49736.325	0.215	1.494	1.431	50090.338	0.291	1.409	1.311
49738.262	0.473	1.450	1.320	50090.358	0.304	1.368	1.355
49788.183	0.917	1.263	1.249	50118.179	0.385	1.466	1.488
49788.208	0.933	1.146	1.153	50118.195	0.396	1.495	1.412
50056.521	0.313	1.336	1.386	50119.166	0.026	1.438	1.425
50056.542	0.327	1.390	1.473	50119.187	0.040	1.415	1.454
50057.288	0.812	1.080	0.936	50119.425	0.195	1.255	1.183
50057.488	0.942	1.247	1.202	50413.404	0.255	1.344	1.344
50057.508	0.955	1.326	1.375	50413.442	0.280	1.359	1.339
50059.388	0.176	1.552	1.358	50414.329	0.856	1.092	1.092
50059.408	0.189	1.312	1.194	50414.353	0.872	1.102	1.095
50060.312	0.777	0.993	1.036	50415.371	0.534	1.382	1.401
50060.325	0.785	—	1.077	50415.396	0.550	1.384	1.349
50060.525	0.915	1.132	1.132	50415.414	0.563	1.311	1.329

Table 4: *Equivalent width measurements of the SiIII lines*

JD	phase	equivalent width (Å)					
		4552		4567		4574	
		LCP	RCP	LCP	RCP	LCP	RCP
50417.487	0.909	0.277	0.285	0.222	0.210	0.117	0.105
50417.513	0.926	0.253	0.248	0.204	0.203	0.113	0.109
50500.251	0.698	0.282	0.280	0.227	0.232	0.109	0.120
50681.558	0.531	0.231	0.216	0.158	0.168	0.094	0.097
50709.550	0.723	0.281	0.288	0.234	0.235	0.128	0.126
50710.492	0.335	0.225	0.193	0.158	0.165	0.083	0.085

ation. Simultaneous variations of LCP and RCP profiles provide strong additional evidence for the absence of large instrumental polarization effects in our spectrograph.

3.3. Variation of SiIII equivalent widths

Moderately strong SiIII λ 4552, λ 4567 and λ 4574 lines are observed in the spectrum of HD 37776. Unfortunately, we have made only a few observations of SiIII, and the phase coverage is not very good. The results of equivalent width measurements of these lines are presented in Table 4 and Fig. 4.

Analyses of Table 4 and Fig. 4 show that our measurements do not contradict Bolender's (1988) results: helium and silicon vary in antiphase, SiIII maximum occurs at phase 0.8. We studied spectral variation of iron using only a weak (4% depth) FeIII λ 5833 line. We have found no variation of its equivalent width with a rotational period larger than the errors of measurements.

4. Magnetic field variations

4.1. Examination of positional accuracy

To check the positional stability of the spectrograph during magnetic observations, we observed regularly the standard magnetic stars: non-magnetic stars and stars with the well-known curve of longitudinal field variations. In addition, as has been said above, we measured the doublet of NaI λλ 5890–5896. Both narrow lines are circumstellar and cannot show any Zeeman shifts, so they were taken as very stable zero-shift test lines for measurements of positional stability. The results of our measurements of NaI λλ 5890–96 line are presented in Table 5.

The obtained shift (difference between the centres of gravity of RCP and LCP profiles) is presented in the units of pixel size of the CCD detector equal to 16 μm.

From Table 5 it can be seen that some instrumental shift (or inclination) is observed. This shift is constant (with uncertainties less than 0.05 pixel) dur-

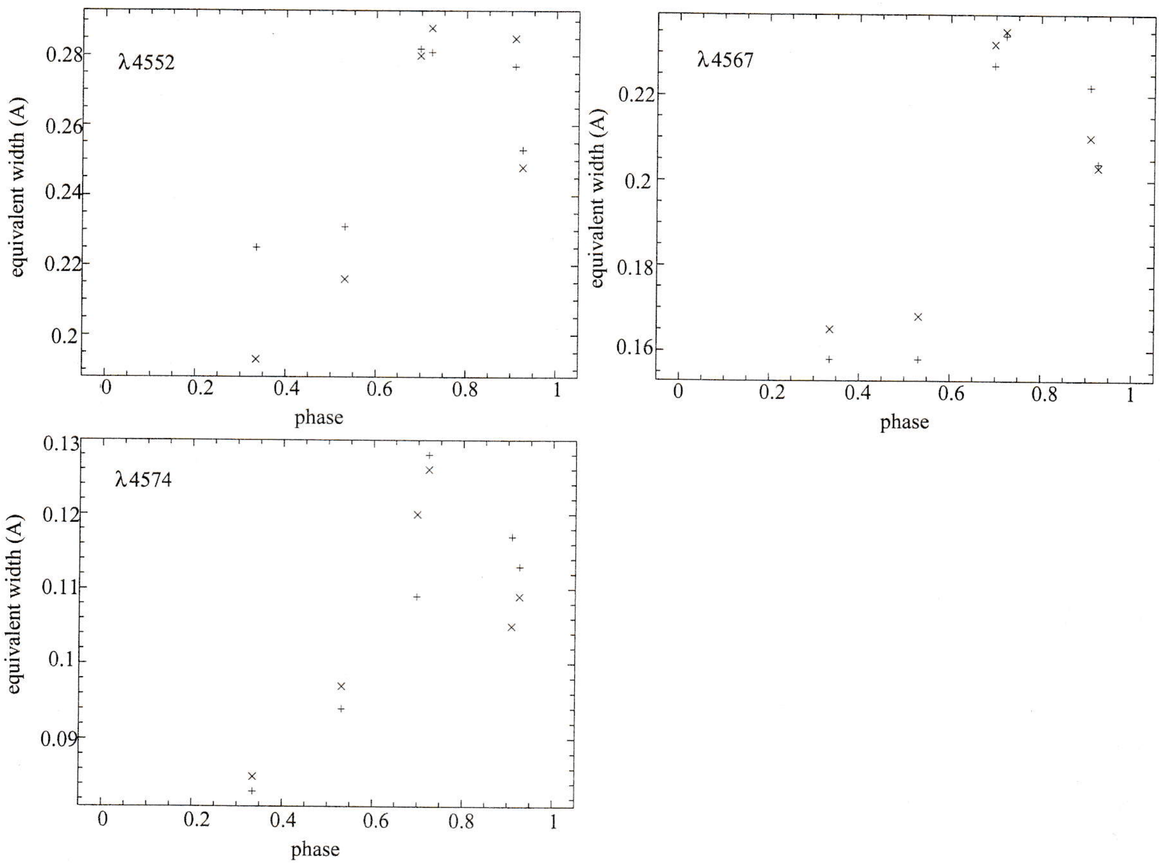

Figure 4: *Equivalent width variations of the SiIII lines (+ – LCP,* x *–RCP profiles,* σ*=20 mÅ).*

ing the same run of observations and therefore can easily be taken into account. The shift is determined by the installation precision of the CCD detector on the spectrograph camera at the beginning of each run of observations. The shift (determined from the NaI lines) is in good agreement with the shift determined from non-magnetic stars.

Our measurements show that we are able to determine the shift correction with an accuracy better than 0.02 px = 0.005 Å, and then we can conclude that the systematic errors of our magnetic measurements, caused by the incomplete allowance made for inclination of the CCD detector, are not larger than ±150 G.

4.2. Longitudinal magnetic field measurements

As noted above HD 37776 has a complex magnetic field structure and a complex structure of line profiles. Thompson and Landstreet (1985) show essentially multipolar field structure using Balmer line measurements. Taking into account possible (widely spread among Ap stars) non-uniform distribution of chemical elements over the star's surface, we expect a very complex picture of the longitudinal field behaviour measured from lines of different elements. Naturally, it is the modelling of polarization profiles that will make possible construction of a magnetic field model of this star. Nevertheless, simple measurements of Zeeman shifts of some lines of different elements may be useful for representation of the general view of the field value and structure of HD 37776.

In Table 6 magnetic measurements of HeI λ 5875 cores, HeI λ 5876 centre of gravity and FeIII λ 5833 total shift (mainly centre of gravity) are presented. Of course, our magnetic shifts presented in this table were produced not only by the longitudinal field (as in the case of polarimetric observations with the Balmer line magnetometer). Our measured field (Table 6) is a mixture of predominantly longitudinal and surface field and therefore a comparison of the data presented with those of Bohlender and Landstreet (1985) is impeded (Fig. 5).

The measurements from Table 6 confirm the complex structure of magnetic field. For example, measurements of HeI line cores show a very large field (tens of kilogauss), while measurements of the centre of gravity of this line (Babcock technique) show a small field. FeIII line measurements show the presence of the field of tens of kilogauss. Fig. 6 shows

Table 5: *Positional measurements of non-magnetic lines (NaI λλ 5890–5896)*

Date	Phase	Shift (pixels) 5890	5896	Average
49736.325	0.215	−0.09	+0.05	−0.02
49738.262	0.473	+0.09	+0.09	+0.09
49788.183	0.917	+0.25	+0.26	+0.25
49788.208	0.933	+0.31	+0.24	+0.27
50056.521	0.313	−0.24	−0.26	−0.25
50056.542	0.327	−0.25	−0.24	−0.25
50057.288	0.812	−0.23	−0.13	−0.18
50057.308	0.825	−0.25	−0.15	−0.20
50057.488	0.942	−0.23	−0.20	−0.22
50057.508	0.955	−0.15	−0.17	−0.16
50059.388	0.176	−0.17	−0.26	−0.22
50059.408	0.189	−0.22	−0.24	−0.23
50060.312	0.777	−0.30	−0.21	−0.25
50060.325	0.785	−0.28	−0.11	−0.20
50060.525	0.915	−0.20	−0.27	−0.23
50060.546	0.929	−0.19	−0.29	−0.24
50087.371	0.362	−0.35	−0.26	−0.31
50087.396	0.379	−0.29	−0.31	−0.30
50088.271	0.948	−0.24	−0.33	−0.29
50090.338	0.291	−0.30	−0.20	−0.25
50090.358	0.304	−0.26	−0.16	−0.21
50118.179	0.385	−0.05	+0.04	0
50118.195	0.396	−0.07	−0.02	−0.05
50119.166	0.026	+0.04	+0.08	+0.06
50119.187	0.040	+0.02	+0.10	+0.06
50119.425	0.195	−0.14	0.00	−0.07
50121.275	0.397	−0.10	−0.07	−0.08
50413.404	0.235	+0.03	+0.01	+0.02
50413.442	0.280	+0.01	−0.02	0
50414.329	0.856	+0.05	−0.01	+0.02
50414.353	0.872	−0.02	−0.01	−0.01
50415.371	0.534	+0.05	+0.02	+0.03
50415.396	0.550	−0.01	0.00	0
50415.417	0.563	−0.02	+0.01	0

the V Stokes parameter distribution over the profile of the HeI λ 5875.7 line in 25 different phases of the period. This figure shows clearly a very complex behaviour of the V Stokes parameter, which indicates a non-dipolar configuration of the magnetic field on the surface of HD 37776. The large value of circular polarization within the λ 5875.7 line profile (V = 5 %!) confirms the existence of a very strong and complex magnetic field. All changes are strictly periodical, which suggests a geometrical (changes of visibilty conditions) but not a physical cause of variability of the magnetic field and line profiles.

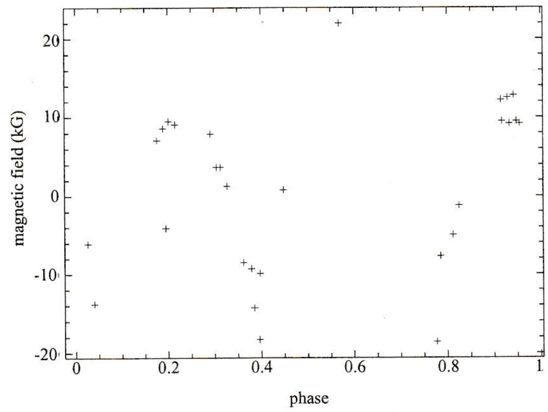

Figure 5: *Variation of the magnetic field measured from the core of He λ5875.7 line. Probable error at each measurement is $\sigma \approx \pm 1kG$.*

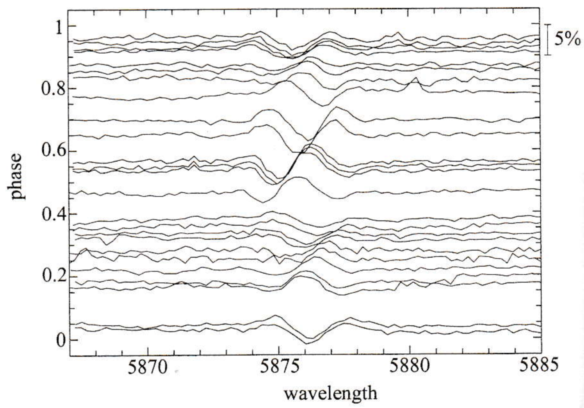

Figure 6: *Distribution of V parameter over the HeI λ 5875.7 line.*

4.3. Surface magnetic field measurements

The fast rotation and complex structure of the magnetic field in HD 37776 make difficult direct observation of Zeeman splitting in the spectral lines. We made an attempt to estimate the surface magnetic field B_s using the Zeeman splitting of SiIII line cores: λ 4552, λ 4567 and λ 4574. Unfortunately, only 5 Zeeman spectra were used for determination. The results of measurements of these lines are presented in Table 7.

From this table it can be seen that our estimates of the surface field by measuring magnetic splitting confirm fairly the large surface field, predicted by Bohlender and Landstreet (1985) and Bohlender (1988). Unfortunately, our data are not sufficient to check the agreement between observations and modelling at other phases of the period.

The very strong magnetic variability has addidional confirmation from the view point of distribution of the V Stokes parameters inside SiIII lines (Fig. 7).

Table 6: *Magnetic field measurements of HD 37776*

JD	Phase	HeI (kG) Core	Center of gr.	FeIII (kG)
49641.471	0.543	+22.0	−0.96	+1.75
49736.304	0.175	+9.5	−2.30	*
49736.325	0.189	+9.1	−3.09	*
49738.262	0.448	+0.8	−5.84	−15.57
49788.183	0.892	+9.5	+0.31	+1.67
49788.208	0.908	+9.2	−0.17	+17.32
50056.521	0.286	+3.7	+0.58	+2.49
50056.542	0.299	+1.3	+1.20	+13.05
50057.288	0.784	−5.0	+0.82	−2.90
50057.308	0.797	−1.2	+1.10	−3.56
50057.488	0.914	+12.8	+1.13	+6.54
50057.508	0.927	+9.2	+1.03	+2.13
50059.388	0.149	+7.1	+0.00	+7.33
50059.408	0.162	+8.6	+1.17	−8.37
50060.312	0.750	−18.6	−1.20	−1.12
50060.325	0.758	−7.7	−0.86	*
50060.312	0.750	−18.6	−1.20	−1.12
50060.325	0.758	−7.7	−0.86	*
50060.525	0.888	+12.2	+1.48	+3.15
50060.546	0.902	+12.5	−3.13	+0.03
50087.371	0.335	−8.5	−0.41	+16.64
50087.396	0.352	−9.3	−0.31	+19.51
50088.271	0.225	+9.5	+1.55	−2.98
50090.338	0.263	+7.9	+4.26	−6.18
50090.358	0.277	+3.7	+1.00	+12.29
50118.179	0.357	−14.3	−0.86	+6.05
50118.195	0.368	−18.3	+0.65	+20.77
50119.166	0.999	−6.1	−0.14	+2.19
50119.187	0.012	−13.8	−1.41	*
50119.425	0.167	−4.1	+3.61	*
50121.275	0.369	−9.9	−0.76	*
50413.404	0.225	*	−1.27*	−2.22*
50413.442	0.250	*	−1.58*	+1.32*
50414.329	0.826	*	−0.52*	−2.24*
50414.353	0.842	*	−1.62*	+0.88*
50415.371	0.504	*	−1.21*	−5.72*
50415.396	0.520	*	−1.49*	−11.16*
50415.417	0.533	*	−1.68*	−8.33*

Table 7: *Magnetic measurements of the Si lines*

JD	Phase	Magnetic field B_s (kG) 4552	4567	4574	Average
50417.487	0.909	28	20	21	23
50417.513	0.926	22	16	24	21
50681.558	0.531	78	48	56	61
50709.550	0.723	56	40	42	46
50710.492	0.335	17	16	21	18

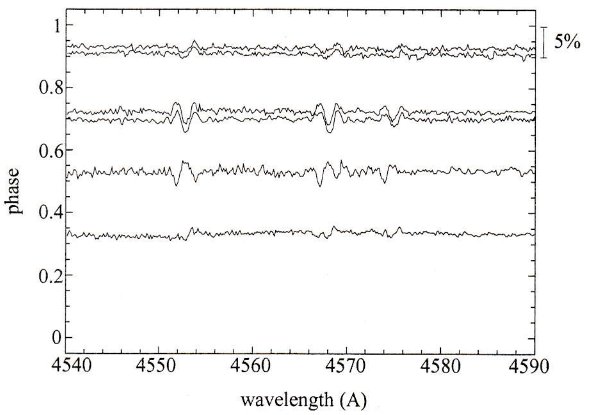

Figure 7: *Distribution of V parameter over the profiles of SiIII lines.*

In this figure the values of the V parameter in the spectral band 4540–4590 ÅÅ containing 3 SiIII lines λ 4552, λ 4567 and λ 4574 at 6 phases of the period are presented. It is seen that the V parameter for these lines changes simultaneously reaching maximum at phases 0.6–0.7. According to approximate estimates, the behaviour of the V parameter with phase of the rotational period for helium and silicon lines agrees well, while equivalent widths of these lines change in antiphase.

5. Discussion of results

In the present paper we report only the first part of our investigation of the magnetic helium-strong star HD 37776. We will continue our investigations for the purpose of constructing a magnetic field model of this unique star. Some results, however, are available at present. These are as follows:

1. Our direct magnetic field measurements show the existence of a very strong (over 60 kG) and complex magnetic field on the surface of the He-strong star HD 37776, which confirms the results of Bohlender and Landstreet (1985) and Bohlender (1988). HD 37776 has the strongest magnetic field among nondegenerate stars which have so far been observed.

2. Helium and silicon lines show a periodical spectral variability with a period of magnetic variations (1.538675 days). This is indicative of the nonuniform distribution of these elements over the star's surface. Helium and silicon vary in antiphase. Our measurements are in good agreement with the previous investigation. Apparently, the effect of magnetic intensification of spectral lines plays an important role in the star with such a strong field and needs to be taken into account when constructing a surface abundance model.

3. Variations of the V Stokes parameter for he-

lium and silicon lines are well phased with the same period. Measurements of HeI λ 5875.7 line cores show double-wave variations with the same period, 1.538675 days. Investigations of Zeeman splitting of SiIII lines indicate directly an over 60 kG magnetic surface field.

4. All variations of equivalent width and magnetic field over the last 10 years have been strictly periodical. The period of variation is 1.538675 days.

5. Our nearest future objective is to construct a magnetic field model for the star HD 37776 and to map the non–uniform distribution of chemical elements over its surface.

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