Zeeman spectroscopy on the echelle spectrometer NES of the 6 m telescope

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Abstract.

Results of first observations with the new echelle spectrometer NES using Zeeman analyzer are presented. For results to be obtained necessary optical and engineering work has been done, software and technique for observations and data processing have been developed. Different instrumental effects are taken into account. Measurements of bright standard stars show that adopted procedure permits us to get intrinsic accuracy of measuring longitudinal magnetic field component B_e of about 5 G. Results of magnetic field determination in a few CP stars are given, including measurements in a hard to access spectral range around Balmer jump (3646 Å), this permits us to study 3-dimensional structure of the magnetic field and distribution of elements over the surface in the stellar atmospheres.

1. Introduction

Search and study of magnetic fields in the Universe is one of the most important problems of present day astrophysics, magnetic observations of different type stars and other objects are included in the observing programmes of world's largest telescopes. Different techniques of studying stellar magnetism exist, but the most effective of them consist in measurements of the Zeeman splitting and polarization of spectral lines formed in the atmospheres of magnetic stars.

It should be noted that for magnetic measurements one needs to use specific devices, which cannot be incorporated in the standard design of telescopes and their spectrographs and therefore these are far from being available at all large telescopes.

The value of the Zeeman splitting in the observed stars is very small, therefore long-term and high-accuracy measurements are required for reliable determination of magnetic field. This is difficult to perform because of the extensive competition of programmes to be carried out at big telescopes.

Investigation of stellar magnetism was always an important direction of astronomical research. For this reason, observation of stellar magnetic fields came to be one of the most extensive observational programmes at the 6 m telescope built in 1975.

By efforts of the researchers and engineers of the observatory the 6 m telescope was equipped with appropriate devices for magnetic field measurements (Bychkov et al., 1988 and references therein). This allowed the domestic astronomers to make magnetic field mesurements beginning in 1977, i. e. from the first days the 6 m telescope came to be operated.

Magnetic field measurements have been made and are being made at the present time with the Main Stellar Spectrograph (MSS) at the Nasmyth focus.

The first-classical Zeeman analyzer with the mica plate retarder (Babcock, 1958) operated in the narrow spectral range (Glagolevskij et al., 1977) did not satisfy us. For this reason, a year later an achromatic analyzer with a Fresnel's rhomb was built (Najdenov and Chountonov, 1976, Glagolevskij et al., 1978). This analyzer has been succesfully operated up to now.

Photographic plates were used as the detector from the first observations to the end of the 80s. A few thousand Zeeman spectra were obtained using the MSS, magnetic measurements of which resulted in discovery of a number of new magnetic stars (e. g. Glagolevskij et al., 1985).

The procedure of photografic magnetic measurements of SAO complied fully with world standard, which was confirmed many times (for example, Wade et al., 1997). After the epoch of photografic observations terminated this technique was no longer used at the 6 m telescope.

At the same time, another procedure of magnetic field measurements was being developed: instead of above described positional measurements of the Zeeman effect (on photographic plates), polarization of lines came to be used.

Two photoelectric magnetometers were operated on the 6 m telescope: the magnetometer with a Fabry-Perot interferometer on the MSS (Glagolevskij et al., 1979) and the prime focus Balmer-line magnetometer (SchtoP et al., 1985). The photoelectric techniques measure magnetic fields of a wider class of objects than previously. A detailed description of our historical instrumentation and techniques can be found in the paper by Bychkov et al. (1988).

Systematic magnetic observations with the new instrumentations — CCD detectors and Zeeman analyzer — were started on the MSS of the 6 m telescope in 1994. In 1991 V. E. Panchuk updated the F-.2.3 camera of the MSS to provide use of a two-dimensional system of photon counting. In 1993 it was adapted for observations with a CCD (Panchuk, 1995), which made it possible to start systematic Zeeman observations.

In the observations of 1994-1996 the CCD detector K 585 (530 x 580 pixels, 18 x 24 μm pixel size, Borisenko et al., 1991) was used. It was installed on the MSS by V. E. Panchuk and his co-workers. The techniques for observations, recording and reduction of data were designed in the laboratory of stellar spectroscopy of SAO (Panchuk, 1995; Galazutdinov, 1992 and others).

In March, 1996 the CCD detector ISD 017A (1160 x 1040 pixels, 16 x 16 μm pixel size) started to be used with the MSS. This CCD was developed especially for magnetic measurements (Glagolevskij and Chountonov, 1997). The techniques of observations on the MSS and their reduction were continuously improved, new codes for Zeeman spectra analyses were developed. The observational procedure with this CCD detector is described in the paper by Romanyuk et al. (1998).

The replacement of the detector alone (a CCD instead of photographic plates) under the condition of permanent use of the Main Stellar Spectrograph and Zeeman analyzer permited us to conserve the system of our magnetic measurements (Wade et al., 1997). At the same time it became clear that progress in observation is possible provided that echelle systems are used.

The history of echelle systems on BTA may be divided into 3 stages according to type of detectors used. The starting complex of detectors of the 6 m telescope incorporated a cross-dispersion spectrograph, installed at the Nasmyth-1 focus (Zandin et al., 1977). This spectrograph was not commonly used for photographic recording (Panchuk, 1998). Beginning with the use of two-dimensional television photon counting systems, this spectrograph was improved and installed at the Nasmyth-2 focus in 1987 (Klochkova and Panchuk, 1991).

This was followed by an autocollimation high-resolution spectrograph ESPAK (Klochkova et al., 1991) which was used at the Nasmyth-2 focus both with the two-dimensional photon counter and with the first Russian CCD detector.

Since 1991 the echelle spectrometer Lynx of the Nasmyth-2 focus (Panchuk et al., 1993) has been used only with a CCD. As the cross-dispersion element, interchangable gratings were employed, and a possibility of observing with the Zeeman analyzer was demonstrated. V. Panchuk and V. Klochkova obtained the first Zeeman spectra using the echelle spectrometer Lynx, but the low level of computing facil-
ities could not implement the capabilities of the MIDAS system.

Of course, it would be extremely ineffective to restrict the reduction of our CCD observations only by measuring the shifts of the centres of gravity of Zeeman line components. The CCD analyzes polarized profiles of spectral lines thus allowing new work of essentially higher level to be performed (Doppler-Zeeman mapping of temperature and chemical inhomogeneities of the star's surface and magnetic field).

The direct confirmation of a very strong (more than 70 kG) magnetic field of complex structure in the helium peculiar star HD 37776 from analysis of polarized line profiles is an example of successful application of the CCD to observations of Zeeman spectra (Romanyuk et al., 1998).

It was impossible to make any rigorous analysis from the photographic spectra obtained earlier (Kopylova and Romanyuk, 1992). Photoelectric measurements of polarization inside the Balmer lines showed only that the structure of the magnetic field of this star was complex (Thompson and Landstreet, 1985).

Undoubtedly, observations with the second camera of the MSS with a spectral resolution of about 0.3 Å are effective for studying separate lines in the spectra of unique stars with broad lines, having complex profiles, where the old techniques could not be used. The MSS is the simplest and reliably tested observational technique, which readily solves the problems with scattered light, determination of location of the continuum and others.

However, the narrow operating spectral range essentially lowers the descriptiveness of work with the MSS: not more than 30-40 lines can be observed simultaneously even in the spectra of the coolest stars because of the small CCD chips, which does not permit high accuracy measurements of magnetic fields.

In the case of hot stars there is a small number of lines in their spectra, this is why to increase the accuracy one needs to observe in different spectral ranges, which requires greater observing time and lowers the efficiency of work.

2. Echelle spectrometer NES

In 1996 an echelle spectrometer PFES was put into extensive operation (Panchuk & Ermakov, 1999). I.D. Najdenov made an achromatic Zeeman analyzer for it. At that time a programme started to enhance possibilities of studying the magnetic fields with a high spectral resolution (Najdenov et al., 1996). An essential increase of the collimated beam diameter is the basis of the programme.

In 1997 a new echelle spectrometer NES with a large collimated beam diameter and updated fast echelle spectrometer Lynx were permanently mounted on the platform of the Nasmyth-2 focus (Panchuk et al., 1999a,b). The spectrometers indicated above have a common with the MSS pre-slit part (Panchuk et al., 1999c), thus along with development of new possibilities, the previous programmes, started with the MSS, could be continued without changes. Study of the positional stability of the NES permits a conclusion to be drawn that its mechanical instability is lower than the recording threshold (Klochkova et al., 1999).

The main performance data of the echelle spectrometer NES can be found in (Panchuk et al., 1999a). For observation with the Zeeman analyzer a special "dekker" containing two diaphragms with the distance equal to the distance between the images of stars is used. Both of them have a width of 0.6 arcsec, and height of 3.5 arcsec. The distance between the images (5 arcsec) is in good coincidence with the distance between echelle orders.

For observations with the circular polarization analyzer in the spectral range 3100-4600 Å a grating of 600 1/mm is used as the cross-dispersion unit; it is more advantageous to use a grating of 300 1/mm for observation in a longer wavelength range. Both gratings have a shaded area 360 x 320 mm in size and are used in the first order.

Note that the transparency of the existing analyzer in the short-wave reqion is low, therefore observations in the UV part of the spectrum were made only for a few brightest stars. We do not present here the format of echelle images for different spectral ranges, because a new CCD of larger size will be installed.

3. Results of magnetic field measurements

3.1. Observation and data reduction

The first observations with the echelle spectrometer NES and Zeeman analyzer were made in July, 1998 in the spectral range from 4800 to 5600 Å. They showed high efficiency of using the new spectrometer for magnetic measurements. Since the autumn of 1998 systematic Zeeman observations with NES have been included in the schedule of observations.

In July 1999 we started to work in a new spectral range 3400-3800 Å, hard to access. As far as we know, there are no Zeeman measurements with a CCD in such short-wave range. But wavelengths around 3646 Å (Baimer jump) are important for measurements because spectral lines on both sides of Baimer lines form at essentially different depth in the stellar atmospheres. This permits the vertical structure of magnetic field and other fine effects to be studied.

CCD 1160 x 1040 px was used as the detector. Observations were made with an achromatic Zeeman analyzer (Najdenov and Chountonov, 1976), adapted for operation with the echelle spectrometer NES.

For reduction of Zeeman spectra we used the programmes described in a separate paper in these proceedings (Kudryavtsev, 2000). The programmes have been designed as a ESO MIDAS context. Although there are standard tools for the reduction of spectral data in MIDAS, we needed to write own programmes when processing Zeeman spectra, because the reduction of such spectra has a number of specific features, therefore the use of some algorithms becomes impossible. Besides, it appeared necessary to develop some algorithms for the secondary spectral reduction — measurements of shifts between lines and so on.

To examine the instrumental parameters of the NES, observations of standard stars were systematically made. Very bright stars, such as Arcturus or Procyon, with a reliably measured "zero" field were used for this purpose.

A reference spectrum of a Th-Ar lamp was taken for each image of the star spectrum with the same position of the telescope: it is used for the identification of spectrum and radial velocity measurements and for determination of instrumental shifts in the spectrograph. For calibration of measurements and their comparison with the international system of measurements, systematic observations of stars with the well-known effective magnetic field B^e variations were made.

This paper is the first report on the Zeeman spectroscopy with the echelle spectrometer NES, therefore here we restrict ourselves only to demonstration of possibilities of magnetic field measurements in a classical sense, i. e. measurements of the centres of gravity. Analysis of polarization profiles is an independent problem which is not considered in this paper.

3.2. Accuracy of magnetic field measurements

We will analyze now the results of examination of instrumental parameters of the spectrograph, precision, and demostrate some new results in more detail.

To investigate the instrumental parameters, high accuracy (S/N over 300-500) observations of bright stars with a large (about 500) number of narrow and sharp lines are needed. Stars without fields are used to reveal false magnetic fields, resulting from the instrumental shift, and stars with the known longitudinal component of the magnetic field are used for taking into account instrumental polarisation, calibration and comparison of our data with the international system of measurements.

The data on standard stars are presented in Table 1.

3.2.1. Non-magnetic standards

Using the Zeeman spectra of the "zero"-field standard Arcturus obtained in the spectral range 4600-5500 A with a high S/N ratio (about 500, see Table 1), we will study instrumental shifts in different orders of the echelle spectrum. Since the lines are inclined (because of inclination of the slit), a false magnetic field may be obtained as result of instrumental shift.

We measured 496 lines, more or less uniformly distributed over the echelle spectra of Arcturus, indicated in Table 1.

Our study (see Fig. 2a in the paper by Kudryavtsev, 2000) shows that instrumental shifts really exist, the value of a shift changes depending on the position of a line on the spectrum. It is convenient to present it quantitatively in units of magnetic field.

The value of a false field, derived from this shift, is —574.6 ± 5.1 G. This is a large shift, which should be taken into account without fail when measuring Zeeman spectra with the NES, not merely subtract as a constant but as a value variable in both coordinates of the echelle spectrum.

Otherwise, the value of the magnetic field measured from one selected sample of lines will in the general case be different from the field value measured from another sample of lines. This may lead to a wrong physical interpretation of measurement results.

We have developed a procedure in which the instrumental shift is approximated by a third degree polynomial and taken into account for each line individually depending on the number of the order and the pixel of its location.

Such a measurement (Fig. 2b in the paper by Kudryavtsev, 2000) shows a value of -0.1 ± 3.4 G. Besides the fact that the field turned out to be zero, which was to be expected after the instrumental shift correction, a certain decrease in the value of the scat-

σr is observed, which is caused by differential taking into account of the instrumental shift value.

Real accuracies of measurements and calculations of differential shifts can be illustrated by 4 observations of the "zero"-field star o UMa, made on January 4 and 5, 1999, when the instrumental set-up of the CCD matrix and Zeeman analyzer was the same. About 500 lines were measured on each spectrum, the S/N ratio was about 200, the spectral range was 4400-5300 Å. The results are presented in Table 2.

Thus, we can introduce a correction of —760 G (as a result of instrumental inclination) in all observations made on January 4 and 5, 1999.

It is readily seen that the scatter of the results of measurement of each separate spectrogram corresponds to their intrinsic accuracy. It follows from our data that the accuracy of measurement of one sharp line on the high S/N (200-300) NES spectra is about 200 G.

When observing on other dates with different setups of the CCD and Zeeman analyzer in the spectrograph, the parameters of instrumental inclination will be different. For example, Arcturus measurements in July, 1998 give a correction of -535 ± 5 G (with S/N=500).

3.2.2. Magnetic field standards

To investigate the instrumental polarization, well-known magnetic stars with a reliably measured B^e values are used. Although an additional investigation is needed, a preliminary conclusion can be drawn that the instrumental polarization of the NES spectrometer is approximately the same as that for the Main Stellar Spectrograph (MSS), mounted at the same focus of the 6 m telescope. It is insignificant in the spectral range around 5000 Å, which is usually used, and begins to increase toward the shorter wavelengths. A study of polarization effects in the NES spectrometer is still in prospect.

The throughput of the Zeeman analyzer and other optical devices in the spectral range of the Balmer jump is essentially lower than around 5000 Å, this is why observations made even under good weather conditions show that the intensity of the recorded spectrum decreases rapidly toward shorter wavelengths.

During a 30 min exposure in good weather it is possible to obtain with NES the spectrum of a 7.5 mag star with S/N ratio 100 in the range 4600-5400 Å, while at the wavelength around 3600 Å during the same exposure time it is possible to obtain the spectrum of very bright (3.7 mag) star β CrB with great difficulties and S/N ratio about 50. This is clearly seen in Table 1. The results of UV measurements will be discussed in more detail later in a separate paper. Comparison of our NES measurements with the previously published data is presented in Fig. 1.

Since Lande factors of more than 90% of actually measurable lines in stellar spectra are inside the range from 0.8 to 2.0 with an average of 1.23 (Romanyuk, 1984), then in establishing whether the star is magnetic or not, there is no need to perform identification.

"Rough" analysis in measuring a sufficiently large sample of lines in any spectral region yields quite reliable results even when the mean Lande factor is used.

However, when studying the detailed structure of magnetic fields of different stars it is necessary to make identification of spectral lines and to determine

Table 1: *Log of observations of standard stars*

Date (JD= 2450000+)	Exposure time, s	max S/N	spectral range	$B_e \pm \sigma$
		standards of "zero" field		
		Arcturus		
14.07.98 (1009.230)	100	450	4600–5500	
24.07.99 (1384.299)	1200	60	3400–3800	
25.07.99 (1385.236)	900	140	3400–3800	
		α Per		
13.08.98 (1039.432)	300	320	4600–5500	
13.08.98 (1039.436)	120	250	4600–5500	
		o UMa		
04.01.99 (1183.224)	300	140	4400–5300	
04.01.99 (1183.231)	600	200	4400–5300	
05.01.99 (1184.104)	300	140	4400–5300	
05.01.99 (1184.107)	100	220	4400–5300	
		magnetic field standards		
		β CrB		
12.08.98 (1038.237)	600	200	4600–5500	-700 ± 24
13.08.98 (1039.253)	600	210	4600–5500	-653 ± 25
14.08.98 (1040.326)	600	430	4600–5500	-496 ± 23
24.07.99	1800	90	3700–3850	-178 ± 67
(1384.322)		40	3450–3600	-481 ± 289
24.07.99	1800	70	3700–3850	-272 ± 113
(1384.346)		30	3450–3600	-104 ± 326
25.07.99	3200	200	3700–3850	-296 ± 43
(1385.291)		80	3450–3600	-439 ± 64
25.07.99	3200	150	3700–3850	-320 ± 53
(1385.330)		60	3450–3600	-334 ± 145
17.02.00	3200		3700–3850	-539 ± 64
(1592.509)			3450–3600	-612 ± 196

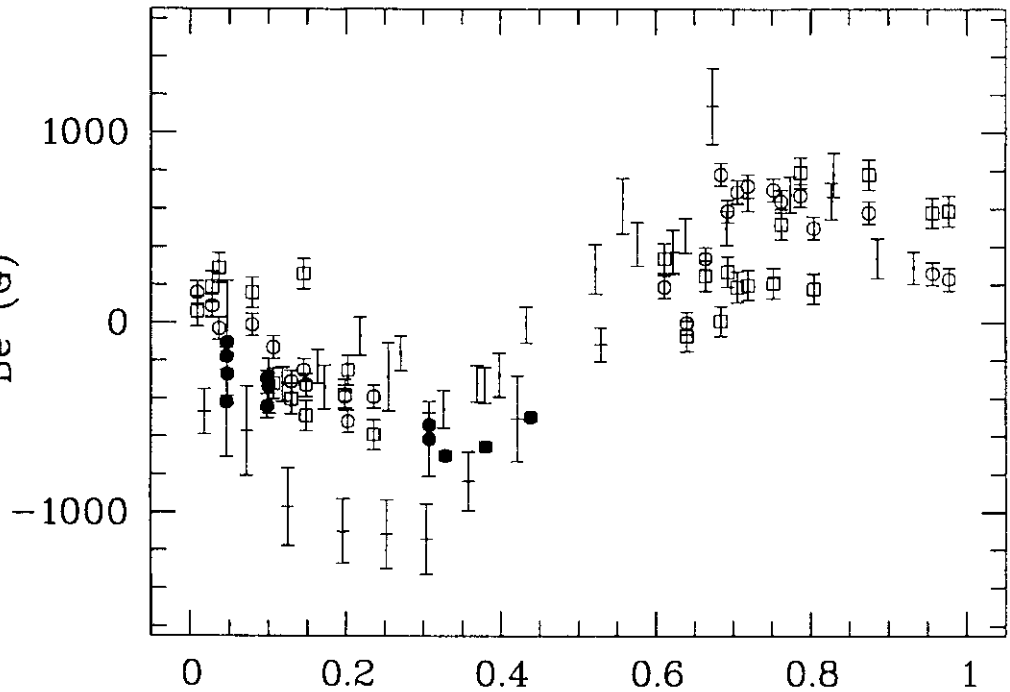

Figure 1: *The effective magnetic field curve of β CrB. Points — photoelectric measurements (Borra and Landstreet, 1980), open circles and squares — photographic measurements before and after Balmer jump (Wolff, 1978), crosses — CCD measurements (Mathys, 1991), solid circles — NES measurements. Phases were calculated using the ephemeris* JD = 2434264^{d}.700 + 18^{d}4868E.

Table 2: *Magnetic measurements of o UMa without instrumental shift correction*

Date	$B(instr) \pm \sigma$	Mean	Δ
4/5.01	-752 ± 8	−760	−8
	-760 ± 8		0
5/6.01	-749 ± 8		−11
	-778 ± 8		+28

magnetic field, taking into account individual Lande factors for each measured line.

Recent creation of the Vienna Atomic Line Database (VALD, Piskunov et al., 1995) introduced fundamental improvements in the process of reduction of Zeeman spectra.

3.3. First results of magnetic measurements

We decided to observe CP stars with well-known curves of the longitudinal field for testing polarimetric devices and search for magnetic fields of new magnetic stars.

We present here, as an example, the results of measurements of the CP star HD 153882. This object of 6.3 magnitude has *vsini* of about 40 km/s, i. e. lines in the spectra are rather broad which complicates measurements and decreases their accuracy. The magnetic field of this star has been measured previously (Babcock, 1958; Hockey, 1971; Mathys, 1991; Mathys and Hubrig, 1997).

Comparison of all measurements shows a large scattering which is possible as a result of complex line structures and large inhornogeneities in distribution of elements on the star's surface. The results of our NES measurements are presented in Table 3.

From Table 3 it follows that the longitudinal magnetic field B_e measured using Cr lines is weaker than that measured from all lines.

Measurements of narrow- and sharp-line CP star HD 12288 (*V* = 7.8 mag) are presented in Table 4. The surface magnetic field of this star was discovered by Mathys et al, 1997.

It is seen that the errors of measurements of the narrow-line star HD 12288 are essentially smaller than in the case of HD 153882. All spectra presented

Table 3: *Magnetic measurements of HD 153882 (V = 6.28)*

Date (JD2450000+)	Phase	$B_e \pm \sigma$	[n]	S/N	Comments
0997.338	0.264	$+3817 \pm 167$	126	140	without ident.
		$+4034 \pm 177$	114		all ident. lines
		$+4260 \pm 246$	76		Fe
		$+3581 \pm 326$	36		Cr
1009.308	0.256	$+3334 \pm 158$	127	165	without ident.
		$+3485 \pm 158$	121		all ident. lines
		$+3534 \pm 201$	86		Fe
		$+3321 \pm 260$	33		Cr
1038.322	0.085	$+2395 \pm 238$	73	70	without ident.
		$+2561 \pm 252$	64		all ident. lines
		$+2517 \pm 292$	41		Fe
		$+2687 \pm 477$	18		Cr
1038.346	0.089	$+3175 \pm 499$	76	40	without ident.
		$+2260 \pm 390$	54		all ident. lines
		$+2395 \pm 457$	38		Fe
		$+1939 \pm 655$	16		Cr
1039.328	0.252	$+3385 \pm 161$	162	130	without ident.
		$+3335 \pm 149$	150		all ident. lines
		$+3399 \pm 188$	89		Fe
		$+3180 \pm 243$	51		Cr
		$+3399 \pm 188$	89		Fe
		$+3180 \pm 243$	51		Cr
		$+4062 \pm 163$	7		Ti

Table 4: *Magnetic measurements of HD 12288 (V = 7.75 mag)*

Date (JD2450000+)	Phase	$B_e \pm \sigma$	[n]	S/N	Comments
51039.404	0.858	-1510 ± 115	104	70	without ident.
		-1704 ± 120	97		all ident. lines
		-1702 ± 184	46		Fe
		-1887 ± 178	40		Cr
		-1050 ± 271	11		Ti
51040.485	0.889	-2440 ± 105	144	150	without ident.
		-2678 ± 92	137		all ident. lines
		-2647 ± 137	66		Fe
		-2799 ± 138	54		Cr
		-2397 ± 278	16		Ti
51184.132	0.005	-2680 ± 113	176	90	without ident.
		-3090 ± 103	161		all ident. lines
		-3087 ± 149	85		Fe
		-3277 ± 151	64		Cr
		-2125 ± 270	12		Ti
51184.163	0.006	-2600 ± 103	173	80	without ident.
		-3060 ± 94	163		all ident. lines
		-3048 ± 138	83		Fe
		-3172 ± 137	67		Cr
		-2595 ± 350	14		Ti

Table 5: *Average values of Lande factors*

Elements	Number of lines	Average Lande factor
Fe	68	1.104 ± 0.045
Cr	65	1.095 ± 0.039
Ti	13	0.969 ± 0.072

in Tables 3 and 4 were recorded in the spectral range 4400-5300 Å.

Check whether the average values of Lande factors for really measured lines of different elements differ from one another. We selected for this purpose the measurements of the magnetic field of HD 12288 made from the best spectrum with a maximum number of identified lines. The results for 3 elements: iron, chromium and titanium are presented in Table 5. It is seen that for our measured sample in the spectral range 4400-5300 Å the average Lande factor is about 1.1. In the case of fast reduction (without identification) of measurements with an average Lande factor of 1.23, the magnetic field will be underestimated by about 15%.

If a star is a spectral variable, for each measurement one may use different set of lines, Lande factors of which can differ essentially, especially for rare-earth elements.

4. Conclusion

The echelle spectrometer NES can be effectively used in observations of stellar magnetic fields.

We present only some possible directions of investigations.

1. Observations of sufficiently bright stars with a high S/N ratio and a high spectral resolution for the purpose of Doppler-Zeeman mapping using a large number of lines. This will permit maps of distribution of different chemical elements over the surface to be produced.
2. Study of fine effects connected with investigation of the magnetic field vertical structure. High accuracy magnetic field measurements from the lines on both sides of the Balmer jump (3646 Å). The use of such spectra will enable construction of a 3-dimensional magnetic field model in the atmosphere of a CP star.
3. In the last few years the multiline technique of observations has been greatly improved (for example, see Wade et al., 1997). The multiline technique finds effectively circular and linear polarization as a cumulative effect of a large number of lines. A study of new class of objects with complex magnetic fields may be possible which improve our knowledge on stellar magnetism.

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