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First Magnetic Stars. New Wine in an Old Bottle.

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Abstract. We present a survey of observational data on the magnetic fields and physical parameters of CP stars for the past 15 years. It appears that the traditional notions on chemically peculiar stars as very stable objects with frozen atmospheres are in need of revision. Analysis of new high-precision observational data allows to detect such subtle phenomena as pulsations of brightness and radial velocities of stars, vertical stratification of chemical elements in their atmospheres. A relationship was found between weak anomalies in the energy distribution in the continuum and the magnetic field strength. An analysis of the Stokes Q and U parameter profiles in the spectral lines of some stars has shown that these observations can be described under the assumption of the field of complex topology, which can not be represented in the form of low–order multipoles. We found large vertical gradients from the lines formed at different optical depths in the stellar atmospheres. These facts indicate much more complex atmospheric structures in chemically peculiar stars than was considered only 15 years ago.

Key words: stellar magnetic fields – chemically peculiar stars – spectropolarimetry

1 Introduction

Approximately 15 – 20 years ago there was a revolution in astronomical observations: CCD detectors started to be in common use instead of photographic plates and photoelectric devices. The researchers of stellar magnetism had an opportunity to search for magnetic fields in new objects, which were not within reach before. Academic interest of many scientists was turned from the study of magnetic fields of Ap/Bp stars to the search for new magnetic stars among other objects. This process was successful: magnetic fields of different strengths and topologies were found in many different stars of our Galaxy.

In this new environment the study of magnetic Ap and Bp stars goes into shadow. Many people believe that nothing essentially new could be achieved in this scientific field. Is this true? Is this a new wine in an old Babcock's bottle?

We have chosen 1995 as a boundary between the old and new observations. Of course, this boundary is not sharp, only being a timescale centre of changing detector types.

Let us briefly recall of the knowledge we had on magnetic CP stars at the epoch of photographic and photoelectric observations.

Approximately 200 magnetic CP stars were known by 1995. The maximal surface field B_s was found in HD 215441 by Babcock (1960). Surface fields from 20 to 30 kG were found for other 3 hot Bp stars. Maximal B_s for cooler Ap stars amounts to 15 kG.

Only 30 sharp–lined stars with strong fields and measured B_s values were known. Therefore, most of the data on magnetic fields were obtained based on the longitudinal field B_e measurements.

The lower limit of B_e detection was approximately 200 G, the field structure — usually dipole, in a few cases — a low order multipole. The stellar model was a simple oblique rotator when magnetic and rotational axes do not coincide. The stellar surface is chemically inhomogeneous. The field origin and evolution: a relic field, no strong evidence of field generation and field decay during the stellar lifetime on the Main Sequence.

Therefore, only 15 years ago we believed that we have confident general idea about the nature of magnetic CP stars and physical parameters they have. These are Main Sequence objects with a mass, temperature, luminosity and radius, typical of normal B and A stars of the same spectral class, and a spectral distribution, corresponding to normal B and A stars.

The main differences consisted in: 1) the presence of a large–scale magnetic field, enveloping the entire star; 2) slow rotation (rotational velocities 3 – 4 times lower than those in normal stars of the same spectral classes); 3) low (20%) occurrence rate among binaries; 4) strong and inhomogeneous chemical composition anomalies; 5) energy distribution anomalies — depressions detected in the continuum.

Over the decades of observations no changes were found in the shapes of photometric, spectral and magnetic variability curves with stellar rotational phase. This indicates a surprising constancy of the atmosphere and an absence of any migration of the spots on the surface.

While the problem of the origin of the field has not been finally clarified, the hypothesis of relic field had stronger evidence. Within this theory the field was formed together with the star during its compression on the stages of evolution to the Main Sequence.

Based on the above–said, the following picture emerged: a magnetic CP star has an atmosphere, "frozen" by the magnetic field, the motion of the plasma in it is possible only along the field lines. In such an atmosphere, the turbulence is suppressed, no flares or explosions occur, the configuration of the chemical spots does not change. Under these conditions very slow (with the velocities of mm/s) processes of selective magnetic diffusion may occur (Michaud, 1970). It results in the formation of spots of chemical elements in different locations on the surface, depending on the topology of the magnetic field.

Still, some facts did not fit into this picture, but they were not as important and plentiful to review it.

2 Main Results of 1995 – 2010 Observations

A detailed survey of magnetic field measurements is laid out in Romanyuk (2010). Let us discuss here only the main results of observations, obtained using the new multi–element digital devices (CCDs) with a high signal–to–noise ratio. Photometric accuracy has increased by more than an order, allowing to analyse not only the averaged line parameters (for example, their equivalent widths), but as well the detailed study of profiles, including the polarization profiles.

A gigantic increase in computing capabilities over the past 15 years has allowed to calculate very complex multi–parameter models of stellar atmospheres, to build synthetic spectra and compare them with observations. Such an approach has made it possible to find a lot of new and subtle effects, not previously known, thus considerably increasing our knowledge of magnetic CP stars.

2.1 Instrumentation

Over the past 15 years new large telescopes (such as the VLT), highly effective spectropolarimeters, analyzers, and other polarizing devices were put into operation. Let us briefly discuss the main instruments with which the observations of magnetic stars at large telescopes were carried out.

2.1.1 Magnetic Field Observations with the 6-m Telescope

Classical Zeeman spectroscopy was performed at the 6–m BTA telescope with two spectrographs: 1) a high–resolution NES spectrograph ($R = 40000$) and a medium–resolution MSS spectrograph ($R = 15000$). CCD chips are used as radiation detectors. A new analyzer with an image slicer was constructed and mounted on the spectrograph by Chountonov (2004). In the past the NES and MSS spectrographs employed the analyzers without slicers.

During the past 5 years and now the Zeeman observations are mostly conducted with the MSS, while the NES polarization analyzer was seldom used with an echelle spectrometer.

The MSS and all the analyzers are located at the Nasmyth focus of the telescope. The instrumental polarization introduced by the oblique reflection in the Nasmyth focus of the 6–m telescope produces a 5% decrease (Glagolevskij et al., 1977) in the measured longitudinal magnetic field. The longitudinal magnetic field B_e is determined from the Zeeman shift of the orthogonally polarized components of spectral lines. The method was proposed by Babcock (1958).

The data reduction is preformed within the MIDAS LONG context and our own codes (Kudryavtsev, 2000; Kudryavtsev et al., 2006) designed for reduction of Zeeman spectra and measurements of longitudinal magnetic field.

The accuracy of magnetic field measurements depends on the number and sharpness of measured spectral lines. In the case of slowly rotating late Ap–type stars, a standard measurement error amounts to about 100 Gauss.

2.1.2 High–Resolution $\mathbf{I}, \mathbf{Q}, \mathbf{U}, \mathbf{V}$ and Multiline Spectropolarimetry

Practice has shown that weak magnetic fields are much easier to detect by integrating the signal of the Stokes V parameter from many lines, rather than measuring the Zeeman shifts. After the introduction of multi–channel digital detectors several multilinear polarimeters were constructed and are since in effective use during the observations.

The MUSICOS polarimeter was the first of them, it came into operation in the late nineties (Donati et al., 1999; Wade et al., 2000). It was designed to study the linear and circular polarizations. A significant increase of the S/N ratio is obtained using the least–squares deconvolution method (LSD). Many ideas originally designed for the MUSICOS have been developed and implemented in the new high–resolution ESPaDOnS (for the 3.6–m CFHT) and NARVAL (for the 2–m Bernard Lyot telescope) spectropolarimeters (Aurière, 2003). Both these polarimeters turned out to be $10-20$ times more effective than the MUSICOS.

2.1.3 Low–Resolution Stokes V Observations with the FORS1 VLT

There were no high-resolution spectropolarimeters built for the 8–m VLT telescopes. The main objective was a study of the maximal possible number of faint stars in clusters of different age. To this end a low–resolution ($R = 2000$) spectropolarimeter was engineered — the polarimetric mode of the FORS1 VLT (Bagnulo et al., 2002).

The device operates in the spectral region of $3500 - 5800$ Å. It measures the total Stokes V parameter simultaneously with many hydrogen spectral lines in the Balmer series with an accuracy of about 0.1%. Apart from hydrogen, this device can also use other (e. g., helium) lines, especially in the case of fast rotators, hot CP stars.

2.1.4 High–Resolution Spectroscopy with ESO Telescopes

High–resolution UVES VLT and FEROS spectrographs at the ESO continued to perform traditional observations, started by G. Mathys (1991) in order to search for stars with split components and make their detailed study. The FEROS spectrograph was mounted at the 2.2–m La Silla telescope

$R = 110000$. It operates in the wavelength range $\lambda\lambda = 4970 - 7010$ Å. The UVES ($R = 48000$) has been in operation at the VLT telescope in the wavelength range $\lambda\lambda = 3530 - 9220$ Å. Surface magnetic fields B_s are found and studied in the stars with narrow and sharp spectral lines (the width of no more than 0.1 Å). The limiting detectable surface field is around 1.5 kG.

2.2 Main Observational Programs

Let us now discuss the observational programs for the study of CP star magnetism, carried out at the above telescopes and list the main observational results obtained under these programs.

2.2.1 Magnetic Field Observations with the 6–m Telescope

Several large programs studying the magnetic fields in CP stars are carried out at the 6–m BTA telescope.

1. The search for new magnetic CP stars is ongoing among the objects with pronounced continuum depressions (particularly at 5200 Å). The observations are carried out at the MSS with a circular polarization analyzer. The Zeeman spectra were obtained for the 130 candidates and in more than 100 of them magnetic fields were detected (Kudryavtsev et al., 2006; Kudryavtsev & Romanyuk, 2007). Among them there are prominent stars with strong magnetic fields: HD 45583, HD 178892, HD 221936, HD 258686, HD 343872, HD 349321. In some of them the B_e curve differs from the sine wave with the phase of the rotation period.

2. We found a 30% decrease of the B_e value with depth in the atmosphere of a bright magnetic CP star α^2 CVn (Romanyuk et al., 2007) using the high–resolution Zeeman observations with the NES echelle–spectrometer simultaneously before and after the Balmer jump (in the spectral region of $3500 - 4100$ Å). The field decrease with height is observed in all the phases of the stellar rotational period, which indicates the presence of a vertical (radial) field gradient an order of magnitude higher than the dipole in its atmosphere.

3. Since 2008 we perform magnetic field measurements from the metal lines and hydrogen line cores of the same spectra. The data are obtained with the circular polarization analyzer at the MSS. The Zeeman spectra measurements have shown that in 22 out of 23 stars observed, the magnetic field, measured from the hydrogen line cores is $30 - 70\%$ smaller, than the estimate obtained based on metal lines. Since the hydrogen line cores form in higher atmospheric layers, we obtain an independent confirmation of the fact that the magnetic field in the atmospheres of the studied CP stars sharply decreases with height with a gradient of several tenths of G/km, which is much more than that possible in the case of a dipole field (Kudryavtsev & Romanyuk, 2009, 2011).

4. Glagolevskij and Chountonov carried out the measurements of the longitudinal field B_e with the phase of the rotational period to obtain its curve for the stars of different types (e. g. Glagolevskij et al., 2010). Detailed comparisons of physical parameters and chemical composition with the topology of the magnetic field were carried out. The authors discovered that in some cases the fields should have a complex, nondipole structure.

Thus, summing up the classical Zeeman spectropolarimetry at the 6–m telescope, we can conclude that very often the observations can not be explained by a stellar model with a magnetic field of the dipole structure.

2.2.2 Main Observational Programs: MUSICOS, ESPaDOnS, NARVAL

A survey of weak field stars using the LSD method was completed by the MUSICOS group (Donati et al., 1999).

The use of the LSD method has made it possible to reduce the measurement error down to 20 G and below. In a fundamental work by Shorlin et al. (2002) the observations of circular polarization of 74 stars are listed. No evidence of existence of a field in normal, Am and Hg–Mn stars with an accuracy much higher than previously achieved for these objects was found. Weak longitudinal fields (of about 100 G) were found in 25 out of 28 observed peculiar stars (Aurière et al., 2004).

Spectropolarimetric measurements of 14 Ap and Bp stars in all the 4 Stokes parameters were conducted, including the first high–quality observations of linear polarization (Wade et al., 2000). The signal from the Zeeman linear polarization was detected in 5 stars, and only in some magneto–sensitive lines. In general, for the measurements of linear polarization a much higher S/N ratio is required, since the signal of linear polarization is typically $10-20$ times weaker than the signal of circular polarization. Modelling of the obtained results confronted major difficulties, it was not possible to describe the field in the assumption a low–order multipole.

2.2.3 Main Observational Programs: FORS1 ESO VLT in Polarimetric Mode

A study of hot magnetic stars in young open clusters by Bagnulo et al. (2003, 2004, 2006) is the main observational program with the FORS1 in polarimetric mode. The Stokes V parameter is recorded for many lines of the Balmer series of hydrogen and strong lines of helium, silicon and other metals, and then the LSD method is applied to measure the longitudinal magnetic field. There are problems with calibration here.

Bagnulo et al., (2006) have shown that the fields, obtained by the LSD method may vary significantly from the fields, obtained using the classical methods for measuring the orthogonally shifted Zeeman components. Nevertheless the LSD method is very effective for the search of new magnetic stars: The same authors (2006) have found 37 new magnetic stars out of 97 observed hot CP stars, belonging to clusters. Two stars with very strong fields were discovered: HD 66318 — $B_e = 4.5$ kG and NGC 2244–334 — $B_e = 9$ kG. The observations of 138 normal B and A stars were carried out with a typical error of 100 G. None of them revealed a field within the measurement error.

Hubrig et al. (2006) presented the results of measurements of the longitudinal field for 136 stars, but cooler than the objects in the previous program. Magnetic fields have been discovered in 57 Ap stars. A record field for the cool star $B_e = 7.5$ kG was found in HD 154708.

2.2.4 Main Observational Programs: Spectra of Magnetic CP Stars with UVES VLT, FEROS

Apart from spectropolarimetry, the ESO UVES VLT and FEROS spectrographs were used for traditional spectroscopy of stars with strong magnetic fields, searching for and investigating the stars with the split Zeeman components. Note here the research made by Neswacil et al. (2004), which studied in detail the splitting of the Zeeman components from the high resolution spectra in the regions before and after the Balmer jump. An increase in the surface field B_s with height on the order of several hundred gauss has been found for three cool stars. A record strong surface magnetic field for cool CP stars was discovered with the UVES VLT in HD 154708 $B_s = 24.5$ kG (Hubrig et al., 2005).

Split Zeeman components were found in 17 sharp–lined Ap stars based on the data, obtained with the FEROS spectrograph on ESO's 2.2–m La Silla telescope (Freyhammer et al., 2008). A surface field B_s in HD 75049 amounted to 30.3 kG (Elkin et al., 2008).

As a result of the above observations more than 10 stars with surface fields from 20 to 30 kG were found.

3 Magnetic Field Strength Distribution

3.1 General Characteristics

Currently, about 400 chemically peculiar stars with reliably registered fields in the atmospheres are known. From 1995 to 2010 about 200 magnetic stars were discovered. Therefore, the detection rate has tripled as compared to the previous period. Nevertheless, 400 stars make up only about 10% of all the known Ap and Bp stars. For more than 3000 potentially magnetic stars the spectra could not be obtained with the Zeeman analyzer. The question of whether all the peculiar stars are magnetic will be discussed below.

The fact that circular polarization is detected in almost all the spectral lines indicates that magnetic fields in Ap and Bp stars have a high degree of order on large scales. Indeed, if the fields are spotted, like in the Sun, then circular polarization, averaged over the disk would be much smaller than the observed one, since the fields with an opposite orientation cancel each other.

Magnetic fields cover the entire surfaces of stars and the field strength distribution is sufficiently narrow. This can be proven by the following: 1) magnetic fields are observed in all the phases of the rotation period, 2) in stars with completely split spectral lines, a continuum is achieved between the split components, and 3) the split components are rather narrow (Mathys, 2001).

We shall review the structure of magnetic fields in more detail in the following section.

The accuracy of field evaluations varies a lot: the typical measurement errors of the longitudinal component B_e amount to 100 – 200 G at the classical Zeeman measurements, and 20 – 30 G using the LSD method. The accuracy of the surface field B_s measurement is much lower — about 1 kG.

There is a good agreement between the values of magnetic fields obtained both by the classical Zeeman spectroscopy and from the Stokes V parameters. We can say that there is an international system of magnetic measurements, and the results from different observatories are identical. Still, there are differences in data obtained by the multilinear LSD method.

Unfortunately, the surface fields B_s are defined only for a small proportion (approximately 20%) of all known magnetic Ap and Bp stars — they are the objects with narrow and sharp lines, where the split Zeeman components can be found given the fields of more than 2 kG. A sample of such objects does not represent all (especially rapidly rotating) stars. Therefore, we use the data obtained from the measurements of the longitudinal field component.

Consider the field distributions by strength according to the catalogue by Romanyuk & Kudryavtsev (2008). It contains the data on 355 magnetic CP stars. Let us use the histogram of the distribution of the longitudinal field component extrema from there. As the simplest approximation we can adopt the surface field $B_s = 3B_e(extr)$, where $B_e(extr)$ is the extremal value of the longitudinal component (see the details in the above paper).

Figure 1 shows the $B_e(extr)$ distribution for the objects from the sample of Romanyuk & Kudryavtsev. We can see that there is a drop in the number of stars within $B_e(extr) = 0.7$ – 5 kG exponentially. A violation of the exponential dependence outside this range is understood quite simply: 1) not all the magnetic CP stars with fields of less than 600 – 700 G were detected (hence, were not included in the list of Romanyuk & Kudryavtsev (2008). Therefore, the drift of the histogram in the region of weak magnetic fields is due to the effects of observational selection; and 2) there are very few objects in the region of strong (over 5 kG) fields, and hence the capability to analyse the statistical regularities is lost.

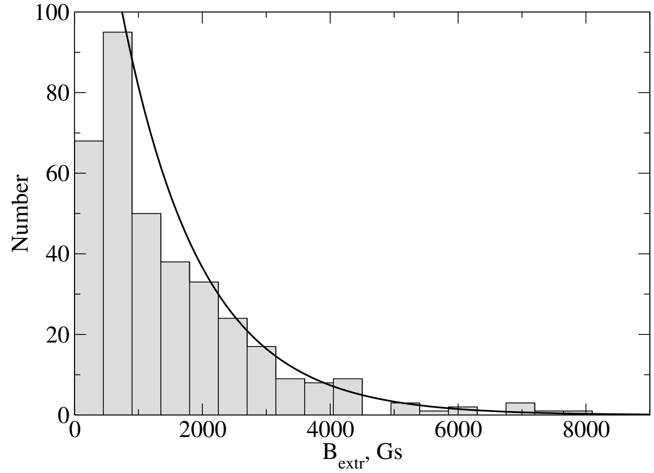

Figure 1: Histogram of the distribution of the longitudinal field extrema $B_e(extr)$

3.2 Lower Limit of Magnetic Field Strength

The question of whether there is a lower limit of magnetic fields is not yet answered. In the classical Zeeman measurements, when the longitudinal field B_e can rarely be measured with an accuracy better than $50-100$ G, no such limit has been found. However, in the past few years, thanks to very precise measurements of the longitudinal component with the MUSICOS, NARVAL and ESPaDOnS instruments a preliminary answer to this question was given: all the Ap and Bp stars possess magnetic fields. Based on their own data Aurière et al. (2008) argue that there is no continuous transition between the magnetic and normal A and B Main Sequence stars. There is a lower limit of about 300 G at the dipole pole, below which the magnetic fields of Ap and Bp stars do not drop. At the same time, none of the normal stars reveal magnetic fields. The conclusions in (Aurière et al., 2008) are based on scarce statistics — only 28 stars. Since there are no other accurate data, we assume that these early data are preliminary.

3.3 The Upper Limit of Magnetic Field Strength

As we already pointed out above, the number of stars with longitudinal fields, with extrema exceeding 700 Gauss decreases sharply with field strength. Romanyuk & Kudryavtsev (2008) believe the field drop law to be exponential, while Kholtygin et al. (2010) believe it is a power law. We assume that so far there is not enough data to accurately determine the field drop law.

Our data demonstrate that in only about 10% of all known magnetic CP stars the surface field strength B_s is over 10 kG.

The maximal measured value of the field was detected for the star HD 215441 by Babcock back in 1960, $B_s = 34$ kG based on the split Zeeman components. For a long time the second largest field $B_s = 18$ kG was found for three objects at once, hence Babcock's star HD 2154441 was outstanding among the other stars by the field strength.

During the past 15 years, about 10 magnetic CP stars revealed surface fields from 20 to 30 kG. Therefore, although HD 215441 continues to be the champion, we can no longer talk about its uniqueness — a gap in the range of $B_s = 20-30$ kG is gradually filled. The modelling of the field of HD 37776 shows that it has a complex topology and can reach up to $60-70$ kG on the surface.

Mathys et al. (1997) studied the distribution of the field modules, averaged over the rotational phase, $\langle B_s \rangle$. In the majority of stars this value lies between 3 and 9 kG with a long tail towards higher fields. But there are no stars detected with $\langle B_s \rangle$ lower than 2.8 kG. This is not the detection limit, we have to observe the field up to 1.7 kG. For some stars $B_s = 2.2$ kG were measured at the minima, but the average field over the whole period does not drop below 2.8 kG.

3.4 Conclusion

We can draw the following conclusions for this section. Magnetic fields on the surfaces of CP stars have the values of 300 G to about 50 kG. A sharp drop in the number of stars, depending on the field strength on their surfaces (at $B_s > 1$ kG) according to the exponential or power law. The observed dependence is smooth, there are no secondary maxima or minima. This means that, in contrast to sunspots, in the atmospheres of CP stars the field strengths are not centered around some typical value.

We see that in the atmospheres of cool stars, like in the sunspots there are no fields of 10 kG or more recorded. Apparently, the local motions (convection, for example) can not generate them. The fields of tens of kG are generated in more powerful processes, covering the entire star in the early stages of evolution during its formation. Thus, we get another indication of the relict nature of the magnetic fields of CP stars.

Evidently, this limit is located on the level of $B_s = 30-50$ kG, beyond which the stronger large–scale fields in the atmospheres of magnetic stars can not form or exist. The absence of fixed (typical) field values indicates that during the star formation there were no fixed mass and velocity values in the motion energy either. The only restriction is that the process energy is such that it allows the generation of fields up to 50 kG.

4 Magnetic Field Topology

4.1 General Remarks

The field of Ap and Bp stars can not possess a spotted structure, similar to the solar one. The fields are global, coherent and differ little in magnitude. Otherwise, the lines in the spectra would be smeared. The sine curve for most of the longitudinal fields B_e is an additional confirmation of this. The split components are very narrow, indicating small variations of the field on the surface (Mathys, 2001).

However, there is a problem here. In the case where B_e changes sign (i. e., we successively observe regions with different polarity of the longitudinal field) — the B_s curve should show a double wave (at the poles of the dipole the field is twice as strong than at the equator). However, the majority of stars demonstrate B_s curves with one wave. This already indicates that the field model in the form of a symmetric central dipole is not standard. We have to make the dipole shifted or noncentral, add a quadrupole and other components. Before considering different models, let us see what do the observations yield.

4.2 CP Stars with Anharmonic Curves of Longitudinal Field $\mathrm{B_e}$

So far only six magnetic CP stars were found with a clearly anharmonic curve of the magnetic field longitudinal component B_e with the phase of the rotational period. Let us discuss them in detail. The physical parameters of stars are taken from our database (Romanyuk, 2004). The links to the original work can be found there. The basic data on the magnetic field are listed below. If a star belongs to a cluster, its age was estimated from the age of the open cluster (the data adopted from Landstreet's catalogue (2010). Otherwise, they are adopted from Kochukhov & Bagnulo (2006), where the stellar ages were estimated from the evolutionary tracks.

4.2.1 HD 32633

This star was designated magnetic by Babcock (1958). As a result of observations with the hydrogen magnetometer, Borra & Landstreet (1980) have found that the photoelectric curve B_e is strong anharmonic, the photographic curve confirmed this result. Extreme values of the field are $-4290\,\mathrm{G}/+1380\,\mathrm{G}$ (the photoelectric curve B_e) and $-5700\,\mathrm{G}/+3500\,\mathrm{G}$ (the photographic curve). A secondary maximum at the phase of around 0.6 is clearly visible. The hydrogen curve is somewhat more sine and slightly shifted in the negative direction, as compared to the photographic one (Renson, 1984).

Further on, high–precision observations with modern multichannel radiation detectors were made. Leone at al. (2010) conducted the observations with a CCD chip. Their curve is very different from the sine, which indicates that the dipole field component clearly does not dominate. Note that Wade et al. (2000) measured the longitudinal field by the LSD method. The curve is in a very good agreement with the hydrogen curve by Borra & Landstreet (1980).

The effective temperature of the star is $T_e = 12580\,\mathrm{K}$, pec=SiCr, $v \sin i = 23\,\mathrm{km/s}$, the rotational period $P = 6\overset{\mathrm{d}}{.}42998$. Kochukov & Bagnulo (2006) have found the star to be very young: its chronological age is $\log t = 6.39$, and evolutional $\tau = 0.00$. The star had only just arrived on the Main Sequence.

4.2.2 HD 35502

The star was found to be magnetic by Borra (1981). The B_e curve with a double wave and a variability period of $P = 1\overset{\mathrm{d}}{.}707$ was built by Glagolevskij & Chountonov (2010). The extrema of the field are $-2250/-95\,\mathrm{G}$ by Borra (1981), and $-5000/+500\,\mathrm{G}$ by Glagolevskij & Chountonov (2010).

According to our data (Romanyuk, 2004) $T_e = 16400\,\mathrm{K}$, pec=He–w, $v \sin i = 58\,\mathrm{km/s}$.

The star is a member of a young cluster Ori OB1a. The catalogue by Landstreet (2010) estimates the age of this cluster as $\log t = 7.00 \pm 0.10$. Let us adopt this age.

4.2.3 HD 37776

A star with an extremely strong field of a very complex structure. The magnetic field is found by Borra & Landstreet (1979), a double wave in the variability curve detected by Thompson & Landstreet (1985). The B_e extrema: $-2000/+2000\,\mathrm{G}$.

The star was studied in detail with the 6–m telescope by Romanyuk et al. (1998). A large Zeeman spectral series was obtained, which confirmed a very complex structure of the circular polarization line profile. A nondipole structure of the star's magnetic field is obvious (see Fig. 2).

The main physical parameters of HD 37776 are: $T_e = 23050\,\mathrm{K}$, pec = He–r, $v \sin i = 80\,\mathrm{km/s}$, $P = 1\overset{\mathrm{d}}{.}538675$.

4.2.4 HD 45583

The star was found to be magnetic with the 6–m telescope. The curve of the longitudinal field component revealed a double wave (Kudryavtsev et al., 2006). The extrema are $B_e = -2500/+3800\,\mathrm{G}$.

Its main physical parameters are: $T_e = 13000\,\mathrm{K}$, pec = Si, $v \sin i = 75\,\mathrm{km/s}$, $P = 1\overset{\mathrm{d}}{.}177000$ (Semenko et al., 2008).

The B_e curve with the phase of rotational period is demonstrated in Fig. 3.

HD 45583 is a member of the NGC 2232 cluster. According to Landstreet's catalogue data (Landstreet, 2010) the cluster age is $\log t = 7.55 \pm 0.10$. Let us adopt the stellar age as 40 Myr. It is hence the oldest chronological object out of 6 stars with complex fields.

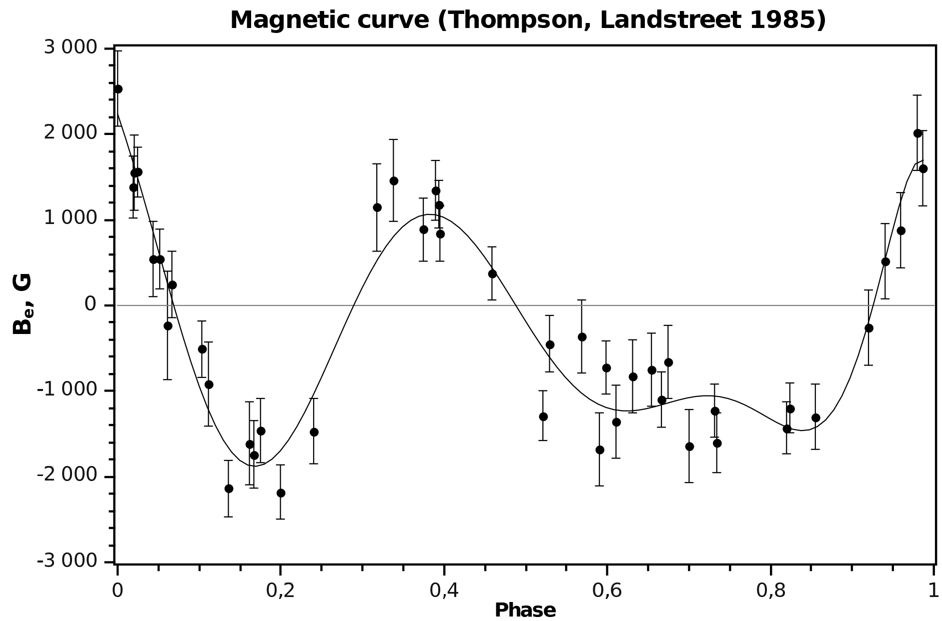

Figure 2: Longitudinal magnetic field B_e phase curve for HD 37776 obtained by Thompson & Landstreet (1985)

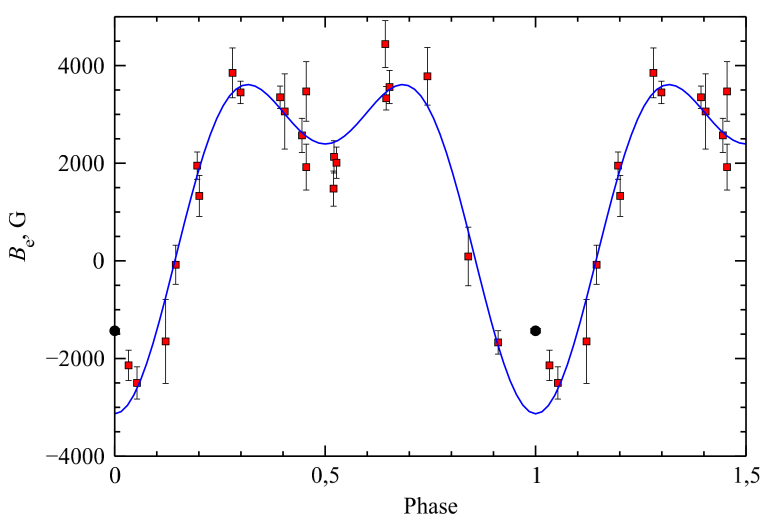

Figure 3: Longitudinal magnetic field B_e phase curve for HD 45583

4.2.5 HD 133880

A strong magnetic field with a nonsinusoidal curve of the longitudinal component B_e variability was found by Landstreet (1990) from the circular polarization in the wings of hydrogen lines. The B_e curve has a nonsinusoidal nature: a very narrow and sharp negative extremum and a gently sloping positive extremum. The variability amplitude B_e ranges from −4440 to +1920 G.

The main physical parameters are: $T_e = 11300$ K , pec = Si, $P = 0.^{\mathrm{d}}8776$. We found no data on the $v \sin i$ value.

Landstreet's catalogue lists it as a member of the Upper Cen Lup cluster (Sco OB2), where the age of the cluster is estimated at $\log t = 7.20 \pm 0.10$. Let us adopt the same age for the star.

4.2.6 HD 175362

The magnetic field was detected by Wolff & Wolff (1976). Borra et al. (1980) found that although the B_e curve is close to sine, there are still some differences: the rate of field variation with time is higher in the field transition from positive to negative than vice versa. The extrema of B_e are from −6860 to +4020 G.

The main physical parameters of HD 175362 are: $T_e = 17000$ K, pec = He–wk, $v \sin i = 28$ km/s, $P = 3.^{\mathrm{d}}67375$.

There is no data on whether the star belongs to any cluster. We adopted the data on the stellar age from Kochukhov & Bagnulo (2006): $\log t = 6.92$, $\tau = 0.06$. Here the age is computed based on the analysis of evolutional tracks.

4.2.7 Discussion of Results

Let us analyse the above demonstrated physical parameters of six magnetic CP stars with a nonsinusoidal curve of the longitudinal component B_e variability. We can see that some common characteristics are inherent to the above group.

1. All the six stars have very strong magnetic fields. The extreme value of B_e reaches 2 kG for HD 37776 and over 4 kG for the five other stars. Given a very complex nature of the field of HD 37776 — the value of the longitudinal component of 2 kG does not adequately reflect its actual value at the surface.

2. All the objects are hot, rapidly rotating stars. The effective temperature exceeds 11300 K, the rotation period is less than a week.

3. All the objects are young stars with ages from 3 to 40 million years.

Of course, the statistics we obtained is still quite scarce. Nevertheless, the data available supports the hypothesis on the relic origin of the field in CP stars. According to this hypothesis, while the star is located on the Main Sequence, the field generation is nonexistent, there is only the ohmic decay of the field on a very long time scale. Small–scale structures, formed along with the star before it appeared on the Main Sequence collapse first of all. Therefore, young stars may possess strong fields of complex topology. During the stellar lifetime on the MS the field decays at a rate proportional to the square of the characteristic size, hence the old stars possess extremely large–scale slowly decaying dipole fields.

4.3 Magnetic Field Topology. Linear Spectropolarimetry

The parameters of linear polarization U and Q are very angle–sensitive. Hence, performing linear spectropolarimetry with high spectral resolution we can explore in detail the behavior of these

Stokes parameters in the line profiles. The faster the rotation — the higher spatial resolution of the object's surface can be achieved.

However, we know that at the magnetic fields, observed in the CP stars, the Stokes Q and U signal is an order of magnitude smaller than the Stokes V parameter signal and has a much more complicated shape. Therefore, high–resolution linear spectropolarimetry is an extremely difficult observational task, it is very time–consuming for the largest telescopes and sophisticated special instruments.

Therefore, at first, the broadband measurements for measuring linear polarization of magnetic CP stars were engineered (Leroy, 1995). The data were compared with the measurements of the Zeeman spectra and overall picture could be made. The simulations showed significant differences from the dipole field topology.

A number of authors found the regions of an open field, where its power lines are open. For example, for HD 192678 the comparison of data of broadband polarimetry and Zeeman measurements of hydrogen and metal lines (Wade et al., 1996) has shown that it possesses a region with an open field at its equator. The field module ratio pole/equator is reduced by 20% compared with the dipole.

For β CrB (Bagnulo et al., 2000) the data on B_e, B_s, the crossover and the broadband linear polarization were analysed. It was found that the field has a very complex picture, which is not explained by the second order multipole.

The question arose about the reliability of model atmospheres for the stars with strong magnetic fields. Wade et al. (2001) 3 programs are compared: Cossam, Invers10 and Zeeman2. At the same input parameters the Stokes I, Q, U, V parameters of the Fe II 4924 line were calculated. The differences were very small, hence, each program can be used. The differences between the obtained profiles are due to the differences in the input data of the atomic and physical parameters, and the peculiarities of the state of the stellar atmosphere structures.

For the first time the analysis of the Stokes I, Q, U, V parameters with high spectral resolution has been made for the star 53 Cam in Kochuhov et al., (2004). The result obtained is that the magnetic topology of 53 Cam is considerably more complicated than any combination of low multipoles.

Kochukov & Wade (2010) detected a very complex field structure for α^2 CVn using the high–resolution measurements of 4 Stokes parameters. These are the multipoles of sufficiently high orders (5 – 6 and above). I am sure that this is a real effect and not a methodological artifact. This is indicated by a good repeatability of results, obtained in one and the same phases of the period. And the same results, obtained using three different programs.

Thus, the scarce observations of linear polarization we currently have in general indicate that the field structure in CP stars is more complicated than the low–order multipoles.

4.4 Vertical Structure of Magnetic Field

4.4.1 Longitudinal Field B_e Before and After the Balmer Jump

For a long time Romanyuk (1984, 1986 and others) demonstrates that for some stars the magnetic field, measured from the lines before the Balmer jump ($\lambda < 3646$ Å) is smaller than the field obtained from the lines after the jump ($\lambda > 3646$) Å. Early photographic measurements are confirmed by the new high–accuracy observations made with the CCDs (Romanyuk et al., 2007). The latter paper shows that the longitudinal magnetic field value B_e in the star α^2 CVn is approximately 30% smaller in the upper atmosphere during all the phases of the rotation period. The measurements were performed from the echelle Zeeman spectra of high spectral resolution, obtained with the NES echelle spectrometer based on a large number of lines in the spectral region of 3400 – 4100 Å. Since the regions before and after the Balmer jump are on the same spectrum, many systematic errors that could affect the outcome were excluded. The results are very reliable. The most natural interpretation is that the field decreases with height in the stellar atmosphere as a whole, with the gradient of about several tenths of G/km, which is at least an order of magnitude greater than the possible difference in the field magnitude (about 1%), taken a dipole field configuration.

The field drop with height is observable as well for the star 53 Cam, but there was not enough data for building the curve.

4.4.2 Vertical Structure of Magnetic Field. $\mathbf{B_s}$ from UVES VLT

The observations of the split Zeeman components in the regions before and after the Balmer jump were carried out with the UVES VLT. For the three cool stars HD 965, HD 116114, and 33 Lib an increase of the field B_s with height by several hundred gauss in the depth of the atmosphere was found by Neswacil et al. (2004).

The main problem here is increased blending with declining wavelength, whereas in the previous case it was the drop in the Zeeman analyzer throughput. The estimates show that none of these reasons can significantly affect the result. We virtually observe either a strong field variability with height, or there are significant gaps in our knowledge of stellar atmospheres in the presence of strong magnetic fields.

4.4.3 Vertical Structure of Magnetic Field. BTA. Hydrogen Line Cores

Kudryavtsev & Romanyuk, 2009, Kudryavtsev & Romanyuk, 2011 present the observations of Ap and Bp stars with large continuum depressions using the BTA MSS with the Zeeman analyzer. The 500 Å–wide spectral range covers both hydrogen and metal lines. Twenty–two of the investigated 23 stars revealed a field drop of about 30% when measuring the shift of the hydrogen line cores in comparison with metals in the same spectra.

We obtained yet another indication of a sharp drop of the field with height. Since the hydrogen line cores are formed in higher layers than metals, we see a systematic field decrease with height at the distance of about 0.1% from the diameter of the star (see the details in (Kudryavtsev & Romanyuk, 2011, presented at the conference).

4.5 Continuum Depressions and Their Link with Magnetic Field

Cramer & Maeder (1980) have found a correlation between the Z–parameter of the Geneva system, which characterizes the depth of depression at 5200 Å. Further research has shown that the correlation is very weak (at 0.5), with a large scatter. The attempts to replace direct measurement of the field by the photometric estimates have not been successful. We can assume the existence of a correlation only in general terms in the analysis of large amounts of data. For example, in Romanyuk et al., (2009) compare more than 200 magnetic stars with large and small depressions in the continuum. The following result is obtained: the RMS field $\langle B_e \rangle = 1341 \pm 98$ G (large depressions) and $\langle B_e \rangle = 645 \pm 58$ G (small depressions). The differences are statistically significant. This means that we can assert with a very high degree of confidence that all the stars with major depressions are magnetic.

Seventy–two new magnetic stars out of 96 candidates among CP stars with strong depressions are the evidence of this fact (Kudryavtsev et al., 2006).

The emergence of a depression is currently interpreted as an anomalous concentration of metal lines in the region of 5200 Å in the spectra of peculiar stars, and a correlation with the field as a result of a magnetic intensification of lines.

If magnetic intensification indeed leads to an increase in the depression intensity, then, in the case of a simple dipole field we should observe a good linear correlation between the field and depressions. Since we only measure the longitudinal component of the field, the scattering may largely be due to a random spatial distribution of the rotational axes and the inclination of the dipole axis to the rotational axis relative to the observer.

The attempts to construct a model of the field and exclude the effect of orientation were conducted several times (e. g. Glagolevskij et al., 1986). They did not lead to success — the scattering has not decreased.

We believe that the lack of a clear linear dependence of the field strength is another indication of its complex topology. The element spots are located in different regions of the stellar surface with a different field (the variations of which are essential, however, do not differ by times, but rather by tens of percent).

4.6 Observational Evidence of Complex Field Topology for Ap/Bp Stars

The fact that the field of Ap/Bp stars can not, in general, be described by a simple symmetrical dipole has long been known. The first attempt to make the model more complex in the form of a non–central dipole was made by Landstreet (1970).

The use of averaged lines parameters (to estimate the values of the longitudinal B_e and surface B_s fields) tends to yield smooth sinusoidal dependencies with the phase of the rotational period. This means that the field, averaged over the entire surface in most cases behaves like a dipole (or is disguised as a dipole field). The existence of several stars with complex B_e curves restrains us to use the low–order multipoles for modelling.

The development of Magnetic Doppler Imaging (MDI) programs allow us to reconstruct the field vector in the relatively small (several tens of degrees in diameter) surface regions. The application of MDI in the spectral analysis of several magnetic CP stars has shown that their fields have a complex and convoluted topology. It can not be described by means of low–order multipoles. For example, Kochuhov et al. (2011) based on data obtained at the BTA, have constructed a new field model for a unique helium star HD 37776. It gives a good description of all types of magnetic observations, obtained for this star.

A study of the vertical structure of the field, carried out by three different methods indicates the presence of a large vertical field gradient, ten times greater than the dipole.

A correlation between the field strength and depression intensity is weak. In general, all researchers have noted a poor correlation between various physical parameters and chemical composition with the stellar field. We believe that the reason for this is its complex structure. The mean values of B_e and B_s characterize it only generally.

All the reviewed techniques indicate the existence of local variations of the field from a few hundred gauss to 1 kG, or an average of $20-30\%$ of the v_e.

What field do we really have? I think that it is individual for each star. There are fine structures, leading to unique patterns of chemical composition anomalies for each star. A fine structure may take the form of local anomalies in the magnitude and direction of the field, but the deviations from the average dipole picture are not as great as in the regions between the spots on the Sun. There is something similar to the hills and dents. Apparently, the higher the spatial resolution, the more confusing the picture we obtain.

A clarification of this issue is extremely important for understanding the physics of stellar magnetism. In the case of a pure dipole field, its gradients are very small. Consequently, the magnetic forces which they produce are very weak too, and hence the efficiency of the magnetic diffusion mechanism (the effect was predicted by Michaud in 1970, but it is not observed in ground–based laboratories) is very weak as well. If the field is complex, then the mechanisms of magnetic diffusion are greatly facilitated. Magnetic gradients evolve, and the requirements for the stability of magnetic star atmospheres become less stringent.

5 Rotation and Magnetic Fields in CP Stars

The relationship between the magnetic field and the rotation of Ap and Bp stars has been investigated plenty of times. It was reliably found that peculiar stars rotate 3 – 4 times slower than normal stars of the same spectral class. On the other hand, a weak statistical pattern was found — hot and fast rotators possess stronger fields. However, kilogauss fields were as well discovered in very slow rotators, such as γ Equ with a rotational period of 80 years. Just as in the case of normal B and A stars, the velocity of rotation of CP stars decreases with decreasing temperature.

It follows that it is necessary to perform a multivariate analysis, since a variety of physical parameters can affect the rotation in many different ways.

Let us consider here only one question — the relationship of the field strength and rotation velocity of magnetic CP stars. Let us fix the temperature range at 8000 – 14000 K, and compare the rotation of stars with large and small depressions in the range indicated above.

It was reliably found that the stars with large (Z, $\Delta a > 0.035$ mag) depressions have their magnetic fields 2 times stronger, manyfold lower velocities, and 3 times longer rotational periods as compared with magnetic stars with weak depressions (Romanyuk & Kudryavtsev, 2008):

Averaged data:

$$v \sin i = 26.0 \pm 2.3 \text{ km/s (large depressions)}$$
$$v \sin i = 48.5 \pm 6.3 \text{ km/s (small depressions)}$$

$$\log P = 0\overset{\mathrm{d}}{.}988 \pm 0\overset{\mathrm{d}}{.}110 \text{ (large depressions)}$$
$$\log P = 0\overset{\mathrm{d}}{.}470 \pm 0\overset{\mathrm{d}}{.}065 \text{ (small depressions)}$$

We have obtained a reliable result — the stars with weak depressions occupy the intermediate position between normal stars and stars with major depressions. The result obtained clearly demonstrates that a slow rotation and strong field help increase the degree of stellar anomaly (both in the continuum and in the lines). It is still difficult to isolate the impact of each of these factors.

6 New Results and New Directions

We can not consider in detail other new results obtained over the past 15 years. Some of them will be presented at our meeting, a gap will hence be filled. Let us list only some of them, the analysis of which requires a revision of established ideas.

1. A large number of new magnetic stars were found in the clusters of different age (Landstreet, this meeting) and in the field. Nevertheless, the well–known stars HD 215441 and HD 37776 are the champions in the field size and strength. A proportion of magnetic stars in young clusters is very small, which could as well be the result of observational selection.

2. Magnetic braking of CP stars on the main sequence was detected. For example, HD 37776 (Mikulasek et al., 2008) has increased its period by 17 seconds within 31 years of observations. At the present time 6 objects are known with slowing down rotational periods. New data are presented in the report of Mikulasek at our meeting.

3. Rapid brightness and spectral fluctuations were discovered in cool magnetic CP stars. An entire new class — the so–called roAp stars (see the report by Ryabchikova, this meeting) was isolated. A vertical stratification of elements, the pulsations of the equivalent widths and radial velocities of lines were discovered. A success in this direction was obtained using the observational data obtained with very high spectral and temporal resolution, and photometric accuracy. This could only be obtained on the world's largest telescopes.

4. A lot of new binary (and sometimes triple) systems were discovered among the magnetic stars using speckle interferometry (Semenko et al., this meeting). It is generally accepted that the ratio of binaries (20%) for magnetic stars is twice lower than that for normal A and B stars. Perhaps the recent results will increase this figure.

Therefore, we see that over the past 15 years there have been significant changes in our understanding of the magnetic Ap and Bp stars. Under the old name, we see other, more complex objects than we previously thought. New high–precision observations have largely contributed to this!

In the near future it will be possible to begin considering another problem. We will have to obtain the B_e curves for dozens of stars in three or four clusters, and construct their field models. It is necessary to analyse not only the magnitude of the field but also the spatial orientation of the rotation axis i and the angle β. We have to see whether the fields and the orientation of the axes in nearby stars are the same.

The first steps in this direction have already been made. We have analysed several closely spaced (a distance of no more than 20 pc) magnetic stars: 49 Cam and 53 Cam; 3 stars in Sco–Cen associations.

The first results are encouraging, we can move in this direction and obtain tangible results. For the above–mentioned stars, we have not only obtained almost identical B_e curves, but also virtually the same chemical composition and orientation of spatial axes (only in the image plane). And the same periods of rotational velocity. If such data will be plentiful, we will be able to answer the question on whether the axes of rotation of nearby stars from the clusters are collinear during their group birth.

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