Open Access Online Journal on Astronomy and Astrophysics
Acta Astrophysica Taurica
www.astrophysicatauricum.org

Acta Astrophys. Tau. 1(2) 26–36 (2020) doi:10.31059/aat.vol1.iss2.pp26-36

Investigations of space magnetism at the Crimean Astrophysical Observatory. II. Direct spectropolarimetric measurements of stellar magnetic fields

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Submitted on June 4, 2020

ABSTRACT

A research on stellar magnetism in Crimea was initiated by pioneer works of A.B. Severny, V.E. Stepanov, and D.N. Rachkovsky. Today, the study of stellar magnetic fields is a key field of research at the Crimean Astrophysical Observatory (CrAO). The 2.6 m Shajn telescope equipped with the echelle spectrograph ESPL, CCD, and Stokesmeter (a circular polarization analyzer) allows us to study the magnetic field of bright stars up to 5^m–6^m.

The Single Line (SL) technique is developed for measuring magnetic fields at CrAO. This technique is based on the calculation of the Zeeman effect in individual spectral lines. A key advantage of the SL technique is its ability to detect local magnetic fields on the surface of stars.

Many results in the field of direct measurements of stellar magnetic fields were obtained at CrAO for the first time. In particular, the magnetic field on supergiants (ϵ Gem), as well as on a number of subgiants, giants, and bright giants was first detected. This, and investigations of other authors, confirmed the hypothesis that a magnetic field is generated at all the stages of evolution of late-type stars, including the stage of star formation. The emergence of large magnetic flux tubes at the surface of stars of V-IV-III luminosity classes (61 Cyg A, β Gem, β Aql) was first registered. In subgiants, the magnetic field behavior with the activity cycle was first established for β Aql. Using the long-term Crimean spectroscopic and spectropolarimetric observations of α Lyr, the 22-year variability cycle of the star, supposedly associated with meridional flows, is confirmed. Magnetic field variability with the pulsation period was first detected for different types of pulsating variables: the classical Cepheid β Aql, the low-amplitude β Cep-type variable γ Peg, and others.

In this review we cover more than a half-century history of the formation of the Crimean scientific school for high-precision direct measurements of stellar magnetic fields.

Key words: magnetic fields, polarization, instrumentation: polarimeters, stars: atmospheres, stars: magnetic fields

1 High-resolution spectropolarimetry at CrAO

CrAO AS USSR has initially been created and developed as an astrophysical observatory. The first tower solar telescope was put into operation in 1954. In 1956, measurements of the longitudinal magnetic field on the Sun were started by A.B. Severny and colleagues using a magnetometer designed at CrAO. In 1961, V.E. Stepanov and colleagues designed, manufactured, and put into operation a vector magnetometer, which allowed one to measure the full magnetic field vector. At the same time a powerful theoretical base was created at CrAO for studying the formation of spectral lines in the presence of the magnetic field in atmospheres of the Sun and non-degenerate stars. The fundamentals were established by Unno (Japan) and V.I. Stepanov (CrAO) in the 50s, and the final solution for approximation of the Milne-Eddington atmosphere model, including magneto-optical effects, was published by D.N. Rachkovsky (CrAO) in 1962 (Rachkovsky, 1962). Since then, astrophysicists have been using the Unno – Rachkovsky equation.

The first successful measurements of the weak stellar magnetic fields were carried out at CrAO in the late 60s of the past century. For the long-slit spectrograph ASP-14 in the coude focus of the 2.6 m Shajn telescope (ZTSh) with one flat diagonal mirror in the light transfer path, a stellar magnetometer with analogue electronics was designed. To this aim, there was modified a construction of the solar magnetograph, operating at the Tower Solar Telescope of CrAO (N.S. Nikulin). The observational results were published in Severny (1970) and Severny et al. (1974).

To calculate the longitudinal magnetic field, an adapted technique for processing solar magnetometric observations was applied: the magnetic field was calculated based on the maximum values of circular polarization in blue and red wings of a spectral line, taking into account calibration of the stellar modulator at the magnetograph of the Tower Solar Telescope based on the sunspot magnetic field. Using this technique, the magnetic field was first recorded for a sample of bright non-magnetic hot and convective stars. Due to the complexity of calibration and imperfection of the first reduction technique, the stellar magnetic field turned out to be strongly overestimated, in some cases by an order of magnitude.

Modern methods for stellar magnetic field measurements using the polarized spectral line profiles significantly surpass the early techniques in the accuracy of measurements. But the first direct stellar magnetic field measurements confirmed the basic hypothesis that the ordinary non-magnetic stars of different spectral types at various stages of evolution have magnetic fields similar to the Sun. Although their fields are by orders of magnitude weaker than those of magnetic stars, they are nonetheless accessible for recording. A new step in the development of stellar astrophysics has begun – the study of magnetic fields in ordinary stars.

In the late 20th century, the first planets were detected for stars. This discovery raised the question concerning the possibility of existence of biological forms of life outside the Solar system. The main criterion of potential planet habitability is a presence of the appropriate atmosphere and liquid water on its surface. The second important criterion is a low magnetic activity of the host star, forming the space weather in the planet's orbit. Otherwise, powerful coronal ejections and high-energy emission from flares are able to destroy the emerging life. Note that on the Sun the probability of very powerful flares and coronal ejections (10^{34}–10^{35} erg) is estimated as one event over 800–5000 years (Obridko and Nagovitsyn, 2017, p. 125). Today, the basic source of information on the possible for this star coronal ejections and flares are direct magnetic field measurements, the epoch of which was opened by A.B. Severny and colleagues with ZTSh at CrAO in the late 60s of the past century.

Since information on the potential level of extreme activity of a star is carried by global and local magnetic fields, the importance of extensive studies of magnetism in astrophysics is obvious. Here it is worth noting the editor quotation at the webpage of the Institute of Aerospace Medicine (Deutsches Zentrum für Luft- und Raumfahrt; DLR): "*Understanding how life appears and finding its evidence elsewhere have become central questions in science*".

In the 70s, instead of the analogous stellar magnetograph, there was designed and manufactured a digital two-channel magnetometer for ZTSh, which was based on counting photons. The new magnetometer simultaneously recorded a spectral line contour scanned by the slit (in the first channel) and a flux from the appropriate region of the conventional continuum (in the second channel). The control over the work of the DKDP crystal that served as an entrance quarter-wave plate was performed with the new magnetograph both on any bright non-magnetic star, using a converter for non-polarized light into the 100%-polarized one in a circle, and by means of a laboratory spectrum of the neon lamp that was put into the magnetic field, the force lines of which were parallel to the telescope optical axis. The processing procedure still had shortcomings and yielded exaggerated values for the longitudinal magnetic field. But the gained experience proved to be very important and was implemented at CrAO while designing and creating the follow-up generation of devices with panorama light detectors (CCD detectors) and for the procedure of high-precision spectropolarimetric measurements of the weak stellar magnetic fields.

A new epoch of weak stellar magnetic field measurements started in the 80s with the appearance of panorama CCD light detectors in astrophysics. In 1985, A.A. Boyarchuk (CrAO) and I. Tuominen (Finland) organized the acquisition from England of the first in the USSR astronomical CCD matrix for ZTSh. In 1986, the first light was acquired with ZTSh (CrAO) using the circular polarization analyzer (Stokesmeter) equipped with a rotating from exposure to exposure quarter-wave plate, a light beam splitter and a CCD served as a spectrum detector. The quarter-wave mica plate was accounted for a region of 6000–6400 angstrom. The Iceland spar crystal was used as a beam splitter. The novelty of the construction lies in the fact that during each consecutive exposure, instead of a spectrum with definite circular polarization, there was projected a spectrum with orthogonal circular polarization. Due to such an approach in the first approximation the instrument errors and sensitivity non-uniformity of matrix pixels are excluded. This was one of the first applications of such a construction that became a standard of spectropolarimetric observations in stellar astrophysics. The first Stokesmeter at the request of CrAO was manufactured by I.D. Naydyonov at SAO AS USSR.

Today, the echelle spectrograph ESPL is being used for spectropolarimetric observations at ZTSh (Lagutin et al., 2019). Observations are commonly carried out in a spectral region of 5000–6900 Å at the spectral resolution R $\sim$51000. The exposure duration is selected in such a way that to obtain a signal-to-noise ratio of single spectra in the intensity maximum in the continuum 250–450. To increase the resulting accuracy, several pairs of exposures are performed. The duration of one exposure is from 120 seconds for 0^m magnitude stars to 1800–3000 seconds for 5^m–6^m objects, depending on the required accuracy. Regular magnetic field measurements of non-degenerate stars of different spectral types at various stages of evolution are implemented at CrAO. These are stars with convective envelopes, magnetic chemically peculiar stars, pulsating stars, hot stars.

2 Methods for spectropolarimetric data reduction

2.1 LSD method

The widely used techniques for measuring magnetic fields from spectropolarimetric observations are modifications of the LSD method, which commonly uses the whole available array of the present in the stellar spectrum spectral lines and blends to derive the weighted mean Stokes profiles (Semel et al., 1993; Donati et al., 1997). This allowed one to increase the signal-to-noise ratio and record weak magnetic fields up to one-tenth of a gauss.

To calculate the longitudinal field according to the LSD method, the following formula is used (Borra and Vaughan, 1977):

$$B_l = 714.53 \times 10^4 \frac{\int \Delta v V_c(v) dv}{\bar{g}\lambda \int [1 - r(v)] dv}, \tag{1}$$

where, for the weighted mean profiles, Δv is the value ($\Delta\lambda_B = 4.6685 \times 10^{-13} \bar{g}\lambda^2 B_l$ (Å)) of energy level splitting of an atom in the magnetic field in velocity units (km/s); $\bar{g}$ is the mean Lande factor of the magnetic splitting, λ is the resulting wavelength and $r(v)$ is the non-polarized contour, V_c

is the normalized to the continuum *V* Stokes parameter. Here $2V_c(v) = r_l(v) - r_r(v)$, where $r_l(v)$ is the left circularly polarized contour and $r_r(v)$ is the right circularly polarized contour of the spectral line.

Using the LSD method, the extensive monitoring campaigns were carried out aiming at searching for magnetic fields in non-degenerate stars of all the temperatures and luminosity classes. For many stars, the field variability with the rotation period was studied, and the magnetic field mapping was performed using the Zeeman–Doppler imaging. But as any other method, LSD has its own limitations in applicability.

The main limitations for applicability of LSD (Plachinda et al., 2019; Plachinda, 2014):

1. The method is applicable only with weak lines and for the analysis of relatively weak fields ($B \leq 1500$ G).
2. Stokes parameter profiles of all the used spectral lines must have a similar shape.
3. Mutually orthogonal Stokes parameter profiles of the same spectral line must have a similar equivalent width.
4. The magnetic field should be homogeneous with the depth of formation of spectral lines.
5. Weighted mean Stokes parameters are integrated from continuum to continuum, i.e. the line wings detected with high uncertainty in the region close to the continuum are involved into the resulting profile that is used for magnetic field measurements.

As is known, spectral lines of non-degenerate stars actually form in various physical conditions which can be caused by:

- spatial inhomogeneity of the temperature;
- spatial inhomogeneity of the gravity force;
- variation of temperature with depth;
- variation of microturbulence with depth;
- variation of density and mass motion velocity with depth;
- spatial inhomogeneity of the chemical composition;
- stratification of chemical elements with depth;
- magnetic field inhomogeneity over the surface and with depth.

Moreover, each star has its own peculiarities and nonstationary processes in accordance with its evolutionary status. Indicators of the complex physical processes in stellar atmospheres are particularly values of energy level splitting of atoms, yielding a statistically significant difference in magnetic field values, a difference in shapes of the Stokes profiles of different spectral lines, and various asymmetries and depths of the mutually orthogonally polarized Stokes profiles of the same spectral line; this is excluded by definition in the LSD method.

Thus, the LSD method is not applicable for the analysis of the complex magnetic topology in the presence of physical and chemical inhomogeneity in the stellar atmosphere (over the surface and/or with depth), in the presence of local magnetic fields (of spots), rapid variability of the magnetic field on timescales comparable in duration with a night observing run.

2.2 SL method (The center of gravity method for individual spectral lines)

To measure magnetic fields, the SL (Single Line) technique was elaborated and has been used for over 30 years at CrAO. It dates back to the ideology of techniques which are applied when processing solar spectropolarimetric data (Prysiazhnyi et al., 2018). The SL method is also based on the Zeeman effect and implies the calculation of distance between the gravity centers of circularly polarized components for each spectral line individually (Plachinda and Tarasova, 1999). Such an approach allows one to calculate the magnetic field from individual spectral lines and to form homogeneous arrays of spectral lines for deriving correct magnetic field values. Despite the labor required, one of important advantages of the SL technique is a capability to detect local magnetic fields on the stellar surface (Plachinda, 2004a).

To calculate from the observed spectra the normalized Stokes profiles with given in advance wavelengths, central residual depths, effective Lande factors and the step size in velocity, the COALA technique was elaborated (Plachinda et al., 2019). This method is workable for both weak lines and strong saturated spectrum lines.

The magnetic field calculation from individual spectral lines is performed through the formula (see, for example, Plachinda, 2014):

$$B_l = \frac{714.53 \times 10^4}{\bar{g}\lambda} \left\{ \left(\frac{\int \Delta v (r^*(v) - r(v)) dv}{\int (r^*(v) - r(v)) dv} \right)_1 - \left(\frac{\int \Delta v (r^*(v) - r(v)) dv}{\int (r^*(v) - r(v)) dv} \right)_2 \right\} \tag{2}$$

where Δv is the effective value of energy level splitting of an atom in the magnetic field in velocity units (km/s); $r^*(v)$ – the limitation function of the used contour part of the absorption line from the side of the continuum in the case of the normalized to the continuum spectra is a constant; $r(v)$ is the function of dependence of the residual intensity on the wavelength, i.e. the contour profile function. Indices 1 and 2 denote the number of the used for calculations two exposures. This formula may be used for the magnetic field calculation based on any contour part.

As an illustration of the influence of inhomogeneous physical conditions at the stellar surface on the profile shape, we may adduce the arithmetic mean profiles I and V for β Aql derived from observations (Plachinda et al., 2019) (see Fig. 1) for spectral non-blended lines, having residual intensity in the range $R_c = 0.68 - 0.72$.

All the array of non-blended spectral lines in the quoted work was divided into two portions due to the fact that the experimental root-mean square error of the whole array of the measured field values differed at the 100 % confidence level from the analogous error ascertained by the Monte-Carlo method, using the normal probability distribution. Thus, different spectral lines of the input array were formed in the presence of different magnetic fields. The division criterion was as follows: lines that yielded the field value which was different more than 3σ from the expected value at a given rotation period phase ($B_e \sim -4$ G) formed one array, and the rest lines were distinguished into another array. The rejected magnetic field values are all of the same positive sign.

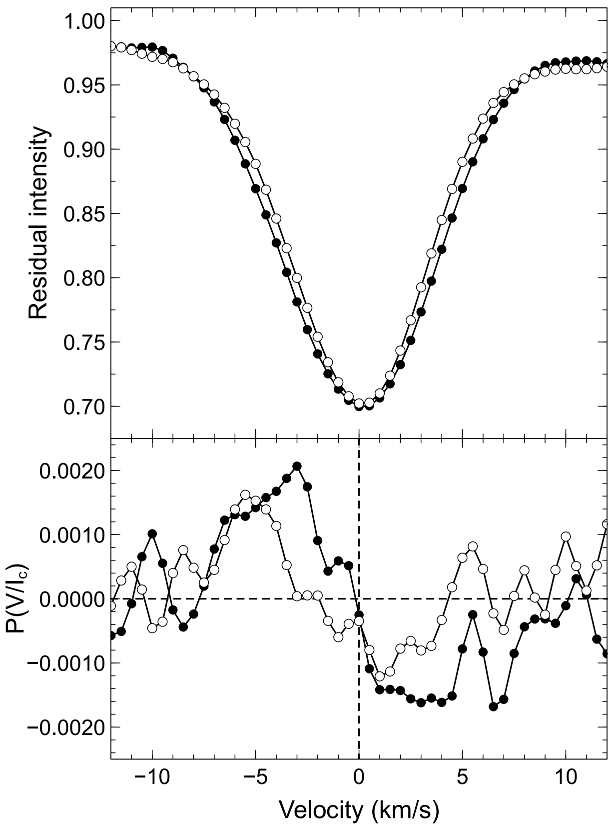

Fig. 1. Normalized Stokes profiles, residual intensity (top panel) and V parameter (bottom panel). Observations were obtained on 06.10.2014. The figure is from Plachinda et al. (2019)

In Fig. 1, the broadened contour (filled circles) corresponds to the mean field value $< B_{\rm e} >= 44.0 \pm 5.6$ G which was derived using 12 spectral lines, falling into the selected averaging range $R_{\rm c} = 0.68 - 0.72$, and the contour denoted by open circles corresponds to the mean field value $< B_{\rm e} >= 12.0 \pm 7.9$ G which is determined based on 5 spectral lines from the given intensity range.

The presented result shows that the construction of the mean profile using all the spectral lines leads to the loss of information on magnetic field inhomogeneities on various spatial scales. The Crimean SL method is free of similar model limitations and allows one to explore local magnetic fields and other magnetic field inhomogeneities both at the stellar surface and with depth of the stellar atmosphere.

3 Stars with evolved convective envelopes

It has been ascertained so far that the primary source of activity on the Sun is a magnetic field. The observed phenomena of activity for stars with convective envelopes are manifestations of the magnetic activity. The most extensive review of more than half a century investigations of activity for the late-type stars of the main sequence is presented in monographs Gershberg (2005), Gershberg (2015), Gershberg et al. (2020).

The minimal errors of photographic and early photoelectric (hydrogen magnetometers) methods for stellar magnetic field measurements are several tens of gauss. Therefore, before the appearance of methods for high-precision spectropolarimetry, the strong fields of magnetic stars with the strength from several hundreds of gauss were predominantly available for astronomers to measure. And just individual high-resolution measurements allowed one to reduce errors up to several gauss and even fractions of a gauss. But this required many-hour exposures for accumulating a necessary signal level. For instance, it took 8 hours of observations at the 1.9 m telescope with a magneto-optical filter to obtain for Procyon ($m_v = 0,34$, Sp F5) a magnetic field measurement accuracy of 0.8 G (Bedford et al., 1995).

When the epoch of panorama light detectors (CCD matrices), echelle spectrographs and achromatic analyzers began, owing to the simultaneous exposure of a number of spectral lines from the near-ultraviolet to near-infrared region, the magnetic field measurements with an accuracy of up to fractions of a gauss for the real observation time became generally accessible. In this case, using the 1.8 m telescope, a magnetic field measurement accuracy of 2.2 G was achieved for Procyon just in 6 minutes (Kim et al., 2007). A brief list of methods for direct stellar magnetic field measurements with references to the original works is outlined in the review by Plachinda (2014).

3.1 Crimean project of survey magnetic field measurements for stars with convective envelopes

Regular spectropolarimetric observations of stars with convective envelopes of different luminosity classes began to be carried out at CrAO in 1989. Namely, the 2.6 m telescope ZTSh was involved, using the Stokesmeter and the long-slit spectrograph. ASP-14 was in the coude focus in the spectral region 6200–6265 Å. The resolution of the derived spectra was $R \sim 3 \times 10^4$ (3.0 pixels), the inverse dispersion – 3 Å/mm, the signal-to-noise ratio in the continuum – $\sim 300 - 400$.

Results of the first survey magnetic field measurements for the slowly rotating stars of I–IV luminosity classes were published in Hubrig et al. (1994), Plachinda and Tarasova (2000), Tarasova et al. (2001), Tarasova (2002), Plachinda (2004a), Plachinda (2004b), Plachinda (2005). Contrary to the RS CVn stars with enhanced activity, where the azimuthal and radial field components achieve 500 G and higher (Donati et al., 2003), for the normal stars from the Crimean survey the longitudinal magnetic field proved to be weak, not exceeding several tens of gauss. In this review, the magnetic field was detected for 21 F9 – M3 stars of all the luminosity classes.

Longitudinal magnetic field variations with the rotation period phase are illustrated in Fig. 2 and 3 for the young similar to the Sun star ξ Boo A (Sp G8 V; $P_{\rm rot}$ = 6.198 days) and old similar to the Sun star 61 Cyg A (Sp K5 V; $P_{\rm rot}$ = 36.618 days). In the first case the variability amplitude is $\sim$40 G, and in the second one it is $\sim$12 G. These are the first solar-type stars for which the magnetic field variability curves with the rotation period phase were obtained (Plachinda and Tarasova, 2000; Plachinda, 2004a).

Of particular interest is also a study of the magnetic field for the supergiant ϵ Gem (Sp G8 Ib). In the early 90s the question remained open as to whether the expanding up to the supergiant stage stars maintain a very weak magnetic field, which is generated through dynamo mechanisms at the

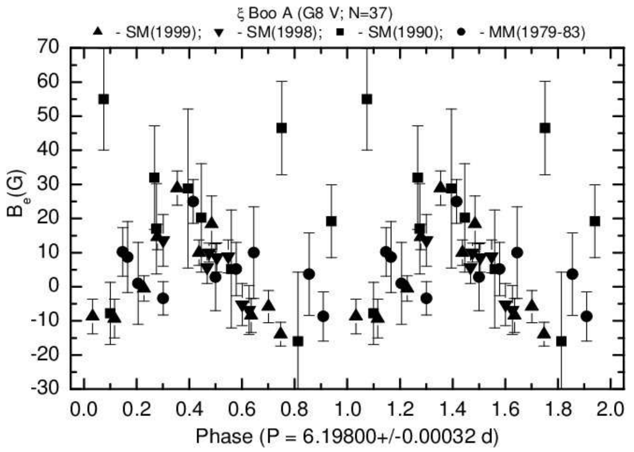

Fig. 2. Variability of the longitudinal magnetic field of ξ Boo A with the rotation period. Years of observations are denoted above the upper abscissa axis: filled up- and down-directed triangles, as well as filled squares are Crimean observations with the Stokesmeter, and filled circles are observations with the multi-slit magnetometer. The figure is from Plachinda and Tarasova (2000)

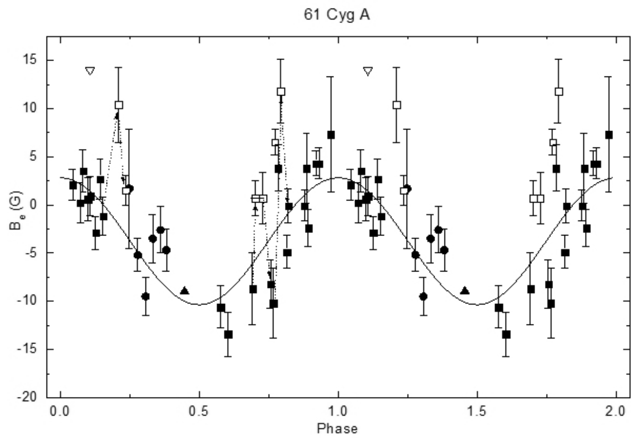

Fig. 3. Variability of the longitudinal magnetic field of 61 Cyg A with the rotation period. Open symbols denote observations that significantly deviate from the fitting curve of dipole configuration. Dotted arrows merge values derived on the consecutive observational dates. Squares and circles are Crimean observations, triangles are observations with the multi-slit magnetometer. The figure is from Plachinda (2004a)

previous stages of evolution, or the dynamo mechanisms keep working at the supergiant stage.

Spectropolarimetric observations of ϵ Gem were carried out during 14 nights between 1994 and 2002. Throughout 5 dates a significant magnetic field was registered in the range from -10 to $+42$ G. A test for a possible influence of instrument effects ("zero" field) for all the dates yielded the negative result; this confirms reliability of the derived values (Plachinda, 2004b). A comparatively large field for ϵ Gem, as well as the detected in the Crimean survey magnetic field of supergiants, giants, and bright giants strengthened the hypothesis that the magnetic field generation for convective stars occurs at all the evolutionary phases up to achieving the degenerate state. Evidence in support of the stated above hypothesis is the fact that the strong, up to several kilogauss, magnetic field in the accretion column was detected for young T Tauri stars (Donati et al., 1997; Johns-Krull et al., 1999a, b), and the measured for active M dwarfs magnetic field modules in spots may achieve 5 kG (Saar and Linsky, 1985; Saar, 1994; Johns-Krull and Valenti, 1996).

Thus, the results of direct measurements allowed one to draw a conclusion that the magnetic field of stars with convective envelopes is generated at all the stages of evolution, including the star-formation stage. The most probable mechanism of generation is dynamo processes.

The subsequent high-precision observational reviews by other authors, as well as a comprehensive study of the magnetic field for the selected objects provided evidence for the presence of the magnetic field in normal stars with convective envelopes of all the luminosity classes. By the 20s of the 21st century an extensive database had been compiled, which included the recorded magnetic fields for stars with convective envelopes. These results allow one to convincingly assert that the magnetic field generation in convective stars occurs at all the stages of evolution.

3.2 Emergence of flux tubes during the active region formation

The results were first obtained at CrAO, which provide evidence for the emergence of large flux tubes in the course of the active region formation for stars of V-IV-III luminosity classes. The emergence of large flux tubes was recorded for 61 Cyg A (Sp K5 V), β Gem (Sp K0 IIIb), β Aql (Sp G8 IV) (Plachinda, 2004a; Baklanova et al., 2011; Butkovskaya et al., 2017a).

To estimate reliability of the recording of magnetic flux tube emergence (Baklanova et al., 2011), a geometrical modeling was carried out concerning the contribution of the magnetic flux of a unipolar spot into the magnetic field of the Sun as a star under the assumption that the radiation transfer in the presence of the magnetic field yields no distortions into the geometrical picture of the stellar magnetic field. Self-consistent parameters of the global stellar magnetic field, spot sizes and their magnetic fluxes were determined by the least-squares method. There was used a linear limb-darkening law with the coefficient $u = 0.55$, the angle between the rotation angle and the line-of-sight was taken equal to $i = 90°$, and the spot width was 30°. A contribution of the penumbra was not taken into account. For the ratio of the radiation intensity in the spot umbra to the undisturbed photosphere, equal to 0.4, at a spot size of 1.5° and the local magnetic field in the spot $B_{\rm spot} = 4000$ G, the contribution of the spot into the mean magnetic field of the Sun as a star is 1 G. This is a real value which exhibits the workability of the selected method. Such an approach allows one to extract a set of solutions which shed light on the spot sizes and their magnetic fluxes for the observed effect to be provided.

The field values at a given spot size were estimated for 61 Cyg A and β Gem. For 61 Cyg A, at $B_{\rm spot} = 4000$ G, the modeled spot size at various input parameters was 4.8°–6.0°. In Fig. 3, open squares show the values that statistically significantly deviate from the global magnetic field curve and

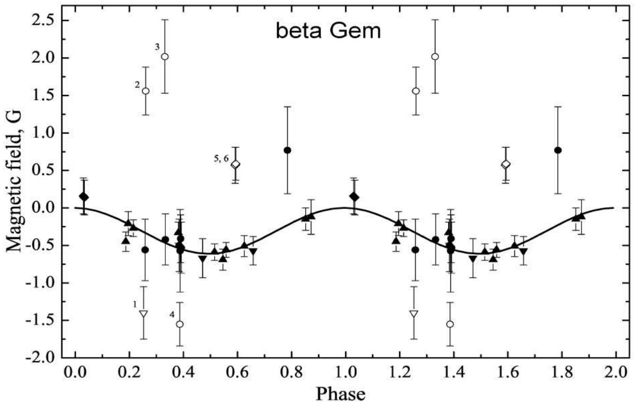

Fig. 4. Variability of the longitudinal magnetic field of Pollux with the rotation period. A description of the figure is given in the text. The picture is from Baklanova et al. (2011)

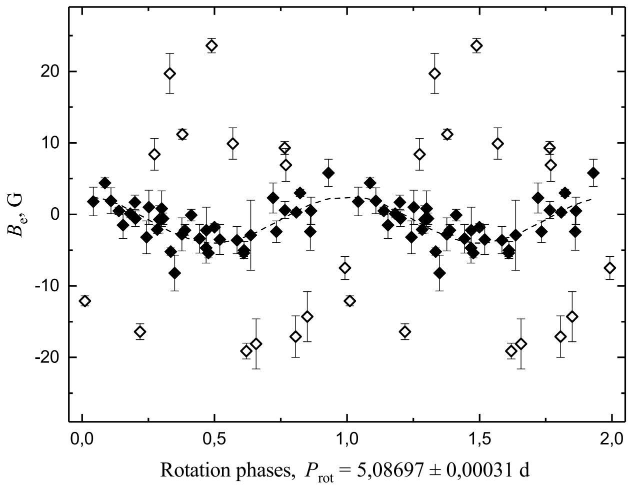

Fig. 5. Average-over-night magnetic field values for β Aql folded in phase with the 5-day rotation period. A description of the figure is given in the text

are likely caused by a notable contribution of emerging flux tubes of the active region (or regions). It is worth noting that all the deviating values are of the same sign, as it should be throughout an activity cycle. Arrows merge values of the consecutive dates. Thus, practically in one day the delaying flux of the other sign is seen to compensate a value of the flux from the emerging tube. This effect is well known from the solar physics.

For β Gem ($P_{\rm rot} = 491.5$ days), at $B_{\rm spot} = 3000$ G, the spot size is $1.0°–1.55°$. In Fig. 4, filled circles denote the observations acquired at CrAO; filled diamonds – observations taken with the 1.8 m telescope at the Bohyeonsan Astronomy Observatory (South Korea); filled triangles – observations from Auriere et al. (2009). Open symbols mark values that deviate more than 3σ. Numbers denote data for which in the quoted work the spot diameter was estimated at a given $B_{\rm spot} = 3000$ G. As in the case of 61 Cyg A, these deviating values may be associated with the emersion of flux tubes on the stellar surface. But contrary to the 61 Cyg A for which observations were carried out over the period that is significantly shorter than the activity cycle and deviations from the magnetic curve were recorded, which are caused by the stellar rotation, but with the positive sign, the observations of β Gem overlap the multi-year time interval; whereas the significant deviations of both signs were recorded.

All the presented in Fig. 5 observations were acquired for β Aql ($P_{\rm rot} \sim 5.1$ days) at CrAO (Butkovskaya et al., 2017a). Points associated with the global magnetic field component are denoted by filled diamonds. The amplitude of the global magnetic field variability with the rotation period is $\sim$3.5 G. The dashed line shows the fitting curve, passing over the filled diamonds by the least-squares method. Open diamonds mark the magnetic field values on the dates when the significant contribution to measurements is apparently made by the local magnetic field associated with the emergence on the surface of magnetic flux tubes of the forming active regions.

3.3 Activity cycle of β Aql

The magnetic field behavior with the activity cycle ($P_{\rm cycle} =$ 969 d) was for the first time ascertained for subgiants (β Aql, Sp G8 IV) at CrAO (Butkovskaya et al., 2017a).

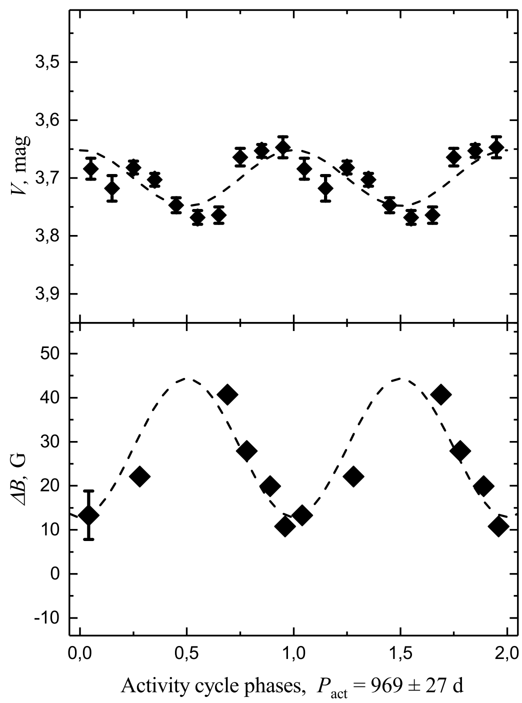

Fig. 6. In the figure for β Aql the top panel exhibits the folded in phase with the 969-day activity cycle and averaged over 10 bins photometric observations in the V filter taken in 2002–2009 within the ASAS project. The bottom panel – variability range (span) of the magnetic field at different phases of the activity cycle from Crimean observations

From Fig. 6 follows that the variability range of the magnetic field is higher at the epoch of brightness minimum.

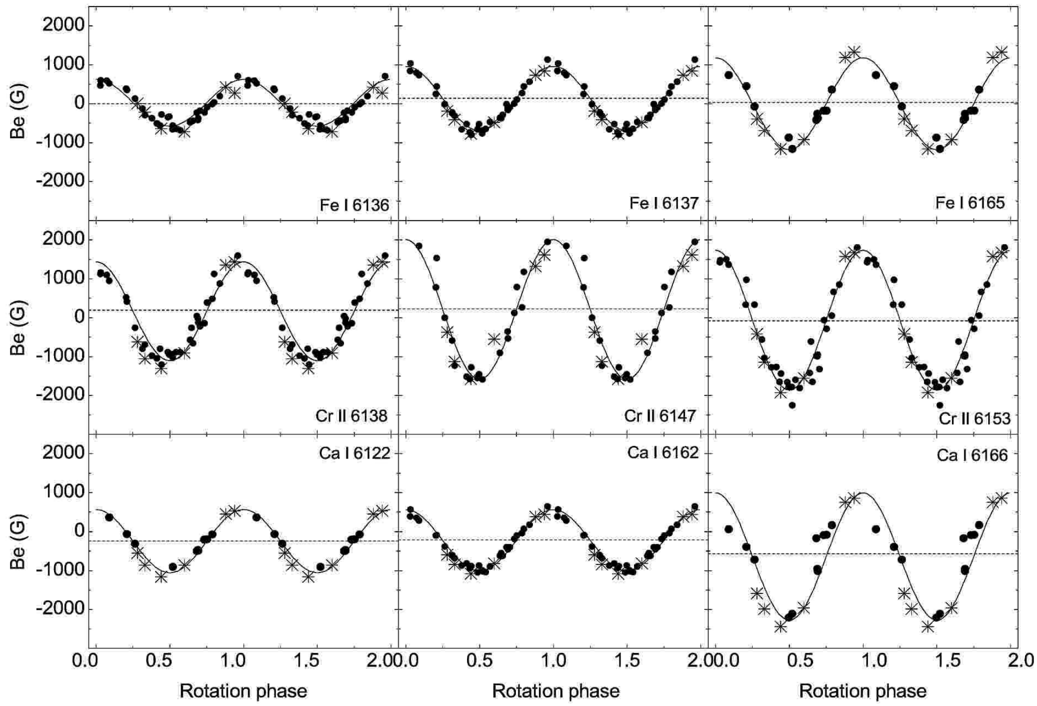

Fig. 7. Magnetic field variability of β CrB with the rotation period that is measured from various spectral lines. Filled circles denote data obtained at CrAO, asterisks – at BOAO (South Korea). Fitting curves drawn by the least-squares method are shown by solid lines. The picture is taken from Han et al. (2018)

Within the framework of the hypothesis by Radick et al. (1998), the anticorrelation of brightness and magnetic activity may be explained by the fact that for β Aql in the activity maximum the radiation deficit in spots dominates over the contribution of faculae into the stellar brightness. Whereas for the Sun this occurs through the domination of radiation from faculae, which yield more contribution into the stellar brightness than the radiation deficit produced by sunspots.

β Aql became the first star for which, contrary to the Sun, an anticorrelation of brightness and amplitude of the global magnetic field variability with the activity cycle phases was ascertained based on direct measurements. This is an important aspect which places emphasis on the necessity of studying magnetic field variability on long-term time intervals, overlapping activity cycles for both the improvement of the dynamo theory and deeper insight into the physics of stellar activity in all.

4 Other stars

4.1 Magnetic field measurement of magnetic stars from individual lines

The problem of local magnetic field registration also remains open for the magnetic Ap/Bp stars with chemical peculiarities. Within the classical notion, the global magnetic fields of Ap/Bp stars are stable on the timescales of several decades and have a simple geometry. In the framework of the inclined rotator model, the magnetic field of Ap/Bp stars is mathematically described typically by the dipole or multipole, the axis of which is inclined to the stellar rotation axis (see, for example, Donati and Landstreet, 2009), and thus at different phases of the stellar rotation period an observer sees different regions of its surface. However, in reality the observed field configuration cannot always be accurately described by the multipole set. This problem is particularly noted by Kochukhov et al. (2004) when studying the magnetic topology for 53 Cam.

To more accurately calculate the magnetic field topology for Ap/Bp stars, the magnetic field measurements from individual spectral lines are required, as well as an account of inhomogeneity of the chemical element distribution in atmospheres of these stars both over the surface and with depth.

β CrB (F2Vp SrCrEuSi). Many-year high-precision magnetic field measurements of the classical Ap star β CrB carried out with the 2.6 m telescope ZTSh at CrAO and the 1.8 m telescope at the Bohyeonsan Astronomy Observatory in South Korea have shown that the magnetic field measured from different spectral lines of the same elements (see Fig. 7), which are in the same ionization state, may have the statistically significantly different mean values and varies with different amplitude with the stellar rotation period (Han et al., 2018). The reason of this effect is not known. One of the possible interpretations is a fast change of direction of the full field vector with the depth of formation of spectral lines in the stellar atmosphere.

33 Lib (F0VspEuGdSr). The inhomogeneity of the magnetic field structure for the roAp star 33 Lib was investigated by Butkovskaya and Plachinda (2019). In particular, the authors revealed that the different spectral lines, including different lines of the same chemical element (see the example

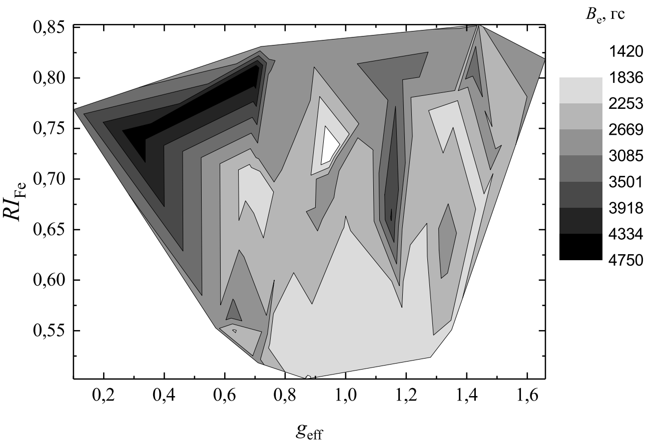

Fig. 8. Calculated from Fe (N = 47) lines dependence of the longitudinal magnetic field on the effective Lande factor g_{eff} and residual intensity RI_{Fe}. The figure is from Butkovskaya and Plachinda (2019)

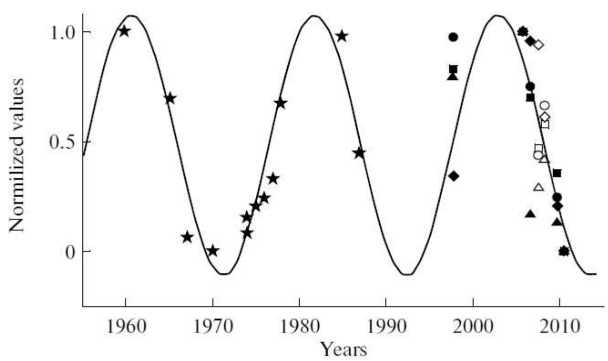

Fig. 9. In the figure before 1990 for α Lyr the normalized values of the extraterrestrial flow that is brought to the wavelength 5556 Å are presented, being derived by different authors (Vasil'yev et al., 1989), and after 1990 there are shown the normalized values of averaged over years equivalent widths of spectral lines of Mg I 5167.321 Å (circles), Mg I 5172.684 Å (triangles), Mg I 5183.604 Å (diamonds), Fe II 5169.033 Å (squares). Filled symbols denote observations carried out with the 2.6 m telescope ZTSh at the Crimean Astrophysical Observatory, open symbols – observations carried out with the 1.8 telescope at the Bohyeonsan Astronomy Observatory in South Korea. The figure is from Butkovskaya (2014)

for the Fe line in Fig. 8), demonstrate a significantly different magnetic field. Higher values of the field are commonly demonstrated by the weak lines with the Lande factor $g < 1$. This may evidence for both the inhomogeneous magnetic field structure in the stellar atmosphere and inhomogeneous distribution of chemical elements over the surface and/or with depth, or for the presence of all these factors. An analogous conclusion was drawn as a result of studying magnetism of the classical Ap star HD 94660 in Bailey et al. (2015).

4.2 Magnetic field of the hot rapidly rotating star α Lyr

The rapidly rotating star α Lyr (Sp A0V) observed from the rotation pole was a commonly accepted photometric and spectrophotometric standard for a long time, and therefore it was extensively observed by various authors and with different equipment. Analyzing spectrophotometric data from various sources, Vasil'yev et al. (1989) suspected a 22-year variability cycle for α Lyr. This value is close to the duration of Hale's magnetic solar activity cycle, which within the transport activity model is determined by the meridional flow cycle on the solar surface. Subsequently, the presence of the suspected cyclicity for α Lyr was confirmed by Butkovskaya et al. (2011) and Butkovskaya (2014) from spectroscopic and spectropolarimetric observations (Fig. 9). Using the data that cover 50 years of observations, the cycle length was ascertained to be equal to 7697 ± 157 days; this is estimated to be 21 years. In the framework of current knowledge, an analogy between Hale's magnetic cycle on the Sun and the detected cycle seems to be impossible, and hydrodynamic calculations of the similar cyclic phenomenon for hot stars are absent in the literature. Therefore, following Merezhin (2001), Butkovskaya et al. (2011) stopped on the assumption that the mechanism that could provide the many-year cyclicity is a meridional flow.

Due to the deficit of data on magnetic fields in normal A stars of the main sequence, the many-year high-precision spectropolarimetric observations of α Lyr were carried out at CrAO; they provided evidence for the presence of the global magnetic field (see Fig. 10).

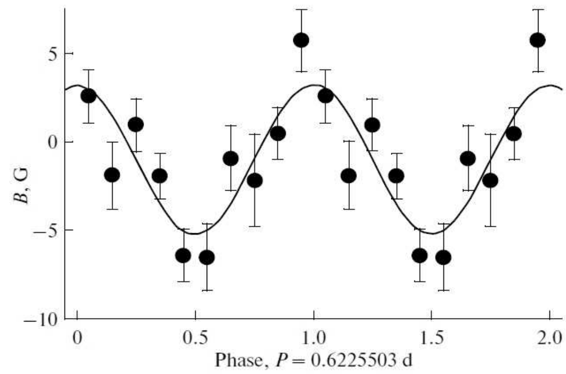

Fig. 10. Variability of the longitudinal magnetic field of α Lyr with the rotation period. 1312 measurements obtained between 1997 and 2010 were averaged over 10 bins. The figure is from Butkovskaya (2014)

4.3 Magnetic field of the close eclipsing binary β Lyr

β Lyr (Sp B8.5Ib-II) is a close eclipsing variable, which became a prototype of the whole class of variable stars. Skulsky (1982) suspected the existence of the magnetic field in β Lyr and its variability with the orbital period phases. It was also assumed that due to the closeness of components the period of the bright mass-losing component may be synchronized with the orbital period. Skulsky revealed that the magnetic field of β Lyrae varies with orbital period phases with an amplitude of 470 G around the mean value −1200 G.

Investigations of magnetism of this binary system were proceeded between 1993 and 2004 at CrAO (Skulsky and Plachinda, 2004) (Fig. 11). Despite a large data

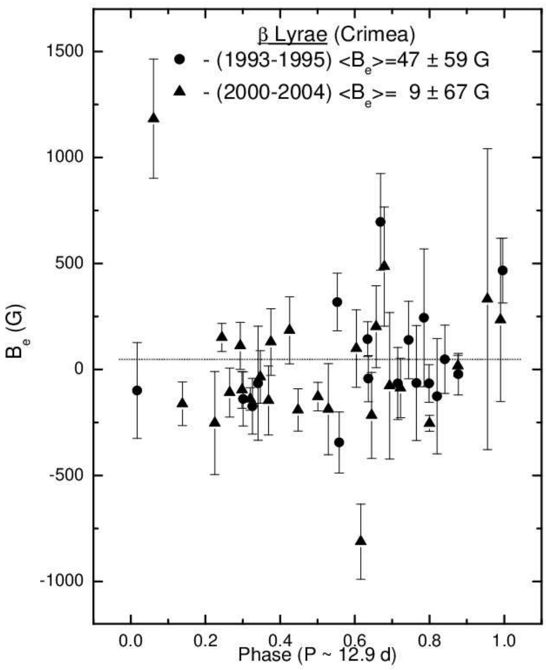

Fig. 11. Magnetic field variability of β Lyr with the orbital period phases. The figure is from Skulsky and Plachinda (2004)

array (N = 44) and the presence of statistically significant average-over-night magnetic field values, it was not possible to ascertain the character of magnetic field variability on this timescale – the overwhelming majority of measurements within the obtained accuracy lie around zero. The ambiguousness of the magnetic field behavior for β Lyr in different years requires a further study. The hypothetic reasons may be: a) a complicated field geometry on the bright mass-losing component; b) difference of the bright component's rotation period from the orbital one; c) physical variability of the magnetic field.

5 Magnetic field variability with the pulsation period

The current observational data and results of theoretical investigations have shown that magnetic fields fundamentally influence the evolution of massive stars, their rotation, structure, dynamics, and stellar wind outflow. Therefore, during the past decade there was a growth of investigations devoted to the magnetic fields of massive stars. Of particular interest are peculiarities of magnetic fields of massive pulsating variables. As far as magnetic fields are detected in these stars, then the question arises on the behavior of the magnetic field, which is frozen-in into the pulsating atmosphere with its large-scale motions, shock waves, etc. Since the 1990s several long-term projects on studying magnetic fields of pulsating stars were carried out at CrAO. The uniqueness of Crimean investigations is primarily in the fact that long-term time series of magnetic field measurements were acquired, which repeatedly overlap the pulsation cycles.

5.1 Classical Cepheid η Aql

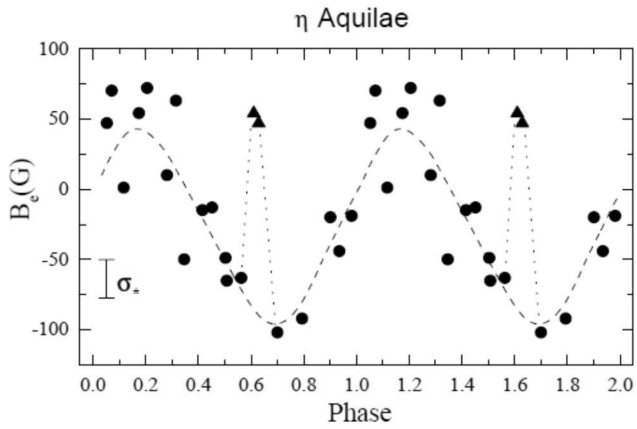

Fig. 12. Longitudinal magnetic field variability of η Aql with phases of the 7.176726-day pulsation period. The figure is from Plachinda (2000)

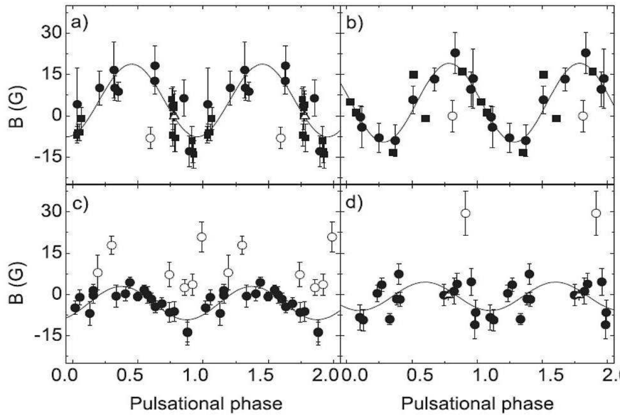

Fig. 13. Longitudinal magnetic field variability of η Aql with phases of the 7.176726-day pulsation period in 2002–2012: (a) filled and open circles: the 2002 observations at CrAO, squares: data from Wade et al. (2002), triangles: data from Grunhut et al. (2010); (b) filled and open circles: the 2004 observations at CrAO, squares: data from Borra et al. (1981) and Borra et al. (1984); (c) filled and open circles: the 2010 observations at CrAO; (d) filled and open circles: the 2012 observations at CrAO, triangles: data from Grunhut et al. (2010). Fitting curves are denoted by solid lines. The figure is from Butkovskaya (2014)

Classical Cepheids are radially pulsating yellow supergiants whose pulsations are driven by the accumulation, with the subsequent penetration outwards, of energy in the ionized helium layer due to the variation of its opacity. The first investigation of magnetic field variability with the pulsation period was carried out for the classical Cepheid η Aql (Sp F6Iab) at CrAO in the late 90s. Plachinda (2000) has unveiled at the 95 % confidence level according to the Fisher test that the magnetic field of the pulsating supergiant varies in the range from -100 to 50 G with phases of the 7.176726-day pulsation period, whereas on nearby dates at the phase 0.6 there are dramatic, accompanied by the sign change deviations of the magnetic field values from the common curve, which can be associated with the passage of shock waves (Fig. 12). Spectropolarimetric observations of η Aql were proceeded at CrAO in 2002–2012. New investigations confirmed the magnetic field variability for the Cepheid with the pulsation period and also revealed that the amplitude of the pulsation variability and field extrema phases vary from year to year (Fig. 13).

5.2 γ Peg – a low-amplitude pulsating β Cep-type variable

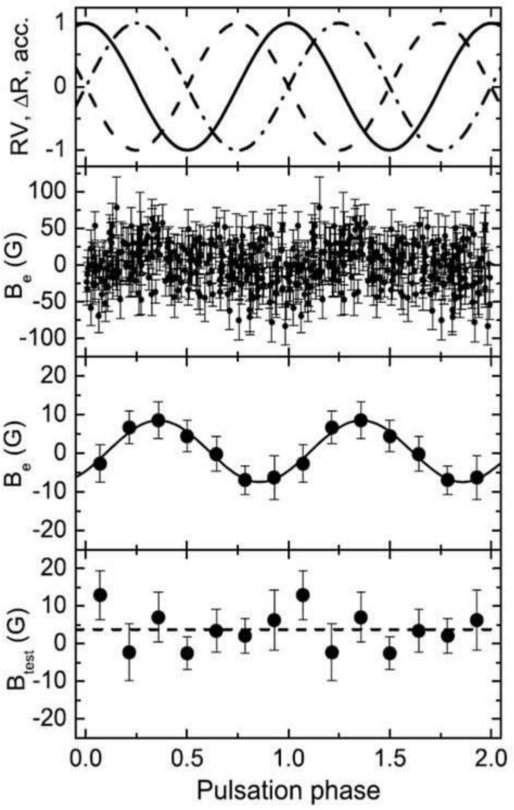

Fig. 14. γ Peg. Top panel: line-of-sight velocity curves (solid line), accelerations (dash-dotted line), and radius variations (dashed line). The next three panels: magnetic field values calculated from individual exposures; magnetic field values averaged over 7 intervals (bins) of the pulsation period (the fitting sinusoid drawn by the least-squares method is denoted by the solid line); averaged over 7 bins test ("zero") field (the fitting line is denoted by the solid line). The figure is from Butkovskaya and Plachinda (2007)

Contrary to the high-amplitude classical Cepheid η Aql, γ Peg (Sp B2IV) is one of the most low-amplitude pulsating β Cep-type variables. The magnetic field variability with the pulsation period was first revealed for γ Peg by Butkovskaya and Plachinda (2007) as a result of many-year spectropolarimetric observations (Fig. 14). Only having a number of observational data which overlap the $\sim$3.8-hour pulsation period, we succeeded in recording the weak pulsation variability of the magnetic field with the full amplitude $\sim$7 G.

5.3 BW Vul – the influence of powerful shock waves on the magnetic field

BW Vul (Sp B2III) is one more pulsating β Cep-type variable. BW Vul pulsates in the radial mode, but contrary to the low-amplitude γ Peg, it has the highest in this stellar type amplitudes of brightness and radial velocity variation. Throughout the pulsation cycle, the powerful shock waves are formed in the stellar atmosphere, which significantly distort the shape and lead to the breaking of the radial velocity curve. The magnetic field behavior of BW Vul with the pulsation period was investigated by Butkovskaya et al. (2017b) based on observations from the open database of the 3.6 m telescope CFHT (ESPADONS). A low signal-to-noise ratio of the polarized spectra did not allow us to estimate the magnetic field with high accuracy. But the phase curves of the magnetic field constructed from different spectral lines made it possible to draw the conclusion that the magnetic field exhibits a complicated behavior with the pulsation period. In a series of curves one can note a significant strengthening of the magnetic field at phases of the presumable passage of shock waves, whereas the curves constructed from different spectral lines exhibit a variation in antiphase. Here we should note that the similar complicated behavior was recorded for 1 Mon – a δ Scu-type variable (Baklanova et al., 2017).

6 Conclusion

The current review reports a half-century history of formation and work of the Crimean scientific school for high-precision spectropolarimetric investigations of stellar magnetic fields. The base of stellar magnetism studies was established in Crimea by A.B. Severny, V.E. Stepanov, and D.N. Rachkovsky.

Since the 80s of the 20th century the regular spectropolarimetric observations of non-degenerate stars of different spectral types and luminosity classes have been carried out at CrAO; these are hot stars, stars with convective envelopes, classical magnetic chemically peculiar stars, pulsating stars, etc. The review presents a series of results from magnetic field investigations of various objects first derived at CrAO in different years.

Investigations of stellar magnetic fields are currently one of important fields of research at CrAO. The up-to-date set of instruments (echelle spectrograph ESPL, CCD, circular polarization analyzer – Stokesmeter) allow one to carry out spectropolarimetric observations of bright stars up to 5–6^m. The polarimetric mode of the spectrograph ESPL in the coude focus was included by the Russian Telescope Time Allocation Committee into the list of scientific programs supported with the 2.6 m telescope ZTSh. The long-term observational programs are preferred at CrAO, which allow one to study the magnetic field variability on various time intervals (hours, days, years).

A new century puts forward new scientific challenges: due to the numerous discoveries of exoplanets, the problem of searching for life in other planetary systems becomes topical. One of the important criteria of the possibility of origination and evolution of life on the planet is a rather low activity level of the host star; the magnetic field is responsible for it. This makes the direct magnetic field measurements be a necessary instrument not only while studying stellar physics, but while searching for the potentially habitable planets.

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