Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
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Long-term stellar magnetic field study at the Crimean Astrophysical Observatory

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Abstract. The long-term monitoring of magnetic cycles is a key diagnostic in understanding how dynamo generation and amplification of magnetic fields occur in solar-like stars. One of the current key problems is the establishment of the magnetic field behavior during the activity cycles for stars of different ages and evolutionary statuses. We present the experience of using own long-term datasets for study of activity cycles in selected stars at the Crimean Astrophysical Observatory.

Keywords. Techniques: spectropolarimetric, stars: atmospheres, stars: activity, stars: magnetic fields, stars: late-type, stars: oscillations

1. Introduction

Era of continuous long-term observations of stellar activity cycles, similar to the solar cycle, began with the pioneering work of Chugainov (1966). He has performed photoelectric observations of the red dwarf BY Dra (K6V) at the Crimean Astrophysical Observatory (CrAO), and proposed that the observed light variations of BY Dra are caused by the presence of a spot on the surface of the rotating star.

The first results of the observations of the General Magnetic Field of the Sun as a star were published in Nature by Severny (1969), who was at that time the director of the Crimean Astrophysical Observatory. Since then, regular observations of General Magnetic Field of the Sun as a star have been carried out at CrAO and other observatories of the world. The duration of the accumulated time series is more than two 22-year Hale solar cycles.

Recent long-term photometric and spectral datasets from ground-based telescopes and satellites allow to obtain rotational periods, butterfly diagrams, S-index behavior, stellar activity cycles, and to study magnetic activity phenomena. To date activity cycles have been detected in hundreds of solar-like stars. One of the current key problems is the establishment of the magnetic field behavior during the activity cycles for stars of different ages and evolutionary statuses. The last question requires long-term time series of the magnetic field measurements.

At the Crimean Astrophysical Observatory regular spectropolarimetric observations in order to obtain direct magnetic field measurements for stars of different spectral classes and luminosity types have been conducted since 1987 using CCD detector, and Stokesmeter in the regime of the circular polarization analyzer. We present our experience of using own long-term datasets for study of activity cycles in selected stars.

2. Observations and data reduction

Before summer 2013 high-resolution spectropolarimetric study of program stellar targets at the Crimean Astrophysical Observatory had been carried out using the long-slit spectrograph ASP-14 (spectral resolution $R \sim 30000$) mounted in the coudé focus of the 2.6-m Shajn reflector. In 2013 it was replaced by the new generation echelle spectrograph with the spectral resolution $R \sim 51000$. In spectropolarimetric mode the achromatic Stokesmeter is mounted in front of the entrance slit of the coudé echelle spectrograph.

To measure the longitudinal component of the magnetic field in a star, we calculate Zeeman splitting of spectral lines, caused by the splitting of atomic energy levels in the magnetic field of the star. If the magnetic field is parallel to the line-of-sight, the original spectral line is divided into two sets of σ components (the π components are not visible in this case). These σ-components have opposite circular polarizations. These two orientations of circular polarization are converted to linear polarization by entrance quarter-wave retarder plate. Then these two linearly polarized modes are separated into two beams by the Iceland spar plate. The output quarter-wave plate converts the linearly polarized light beams to circularly polarized light. This balances the difference in the reflectivity of these two light beams from the diffraction grating. To avoid possible instrumental effects, the entrance quarter-wave plate is rotating by 90° between two subexposures, and the positions of the polarized spectra on CCD are exchanged. Today we have the opportunity to explore the magnetic fields of stellar targets brighter than 6^m.

The wavelength displacement of σ components from its original wavelength:

$\Delta\lambda_{\rm B} = (e/4\pi m_e c^2) z\lambda^2 B_{\rm e} = 4.67 \times 10^{-13} z\lambda^2 B_{\rm e}$

where e is the elementary charge, m_e is the electron mass, c is the speed of light, z is the effective Landé factor, λ is the wavelength in Å, and $B_{\rm e}$ is the longitudinal magnetic field in Gauss.

The spectral region 5000–6900 Å is typically used in our investigations. The signal-to-noise ratio of a single spectrum is 250–450. In order to increase the signal-to-noise ratio we obtained several sets of subexposures of the object during the night. The single exposure time varies from 120 seconds for targets of 0^m to 1200–1800 seconds for targets of 5–6^m.

Designed at the Crimean Astrophysical Observatory software for magnetic field calculation (see Butkovskaya & Plachinda 2007 for more details) allows us to measure magnetic field using unblended single spectral lines as well as all bulk of suitable lines in the stellar spectrum.

3. Long time-series for magnetic activity study

61 Cyg A (HD 201091, K5V, $V = 5.2^m$) is a moderately active solar-like star with vigorous convective envelope. The star belongs to BY Dra variables, which luminosities vary over stellar rotation period due to star spots, and other chromospheric activity. Plachinda (2004) using own long-term spectropolarimetric observations collected over 34 nights from Jule 1998 to September 2002 found that the longitudinal magnetic field of 61 Cyg A varies over rotational period 36.618 ± 0.061 days with full amplitude ~15 G (from −10 to 5 G approximately). He also reported the detection of the unipolar spot emergence on the surface of 61 Cyg A (see also Plachinda *et al.* 2011). Boro Saikia *et al.* (2016) reconstruct the large-scale surface geometry of 61 Cyg A for six epochs over nine years of observations and report the presence of a possible magnetic cycle which is twice the length of the activity cycle. They concluded that the evolution of the large-scale field of 61 Cyg A over the activity cycle shows close resemblance to the solar large-scale field.

DE Boo (HD 131511, K5V, $V = 6.0^m$) is a spotted variable of RS CVn type. These stars are close binary systems having active chromospheres and large stellar spots, which are believed to cause their observed luminosity variations. Spectropolarimetric

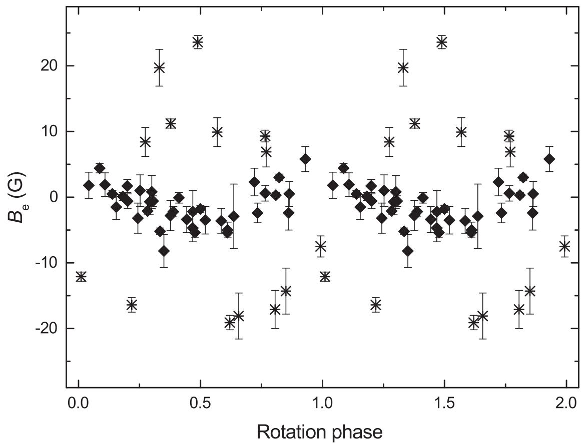

Figure 1. Large-scale magnetic field of β Aql (rhombs) and possible local magnetic field manifestations (stars) folded in phase with the 5.1 d rotation period.

observations of DE Boo have been performed at the Crimean Astrophysical Observatory over 18 nights in 2001-2004. It was founded that the longitudinal component of the magnetic field varies from 44 G to -36 G with mean Standard Error (SE) of 8.2 G (see also Plachinda *et al.* 2017). Unfortunately, our magnetic time-series and the accuracy of the measurements are not enough to study the variability of the magnetic field with the 10-day axial rotation period of DE Boo. Now the spectropolarimetric monitoring of DE Boo at CrAO is suspended.

η Boo (HD 121370, G0IV, $V = 2.7^m$) is a yellow subgiant with thin convective envelope. Spectropolarimetric observations of η Boo have been performed at CrAO over 50 nights from 1999 to 2014. The longitudinal magnetic field was found to be variable from -15.1 ± 6.4 G to 23.1 ± 9.6 G (see also Butkovskaya *et al.* 2018). The statistically significant magnetic field was detected over 5 out of 50 dates. The best errors of the magnetic field measurements are less than 1 G. But the mean error is $\sim$5 G, whereas most of the $B_{\rm e}$ values fall in the range from about -5 to 10 G. So, to identify large-scale and small-scale components of the magnetic field of η Boo longer and more precise measurements are required.

β Aql (HD 188512, G8IV, $V = 3.7^m$) is a yellow subgiant with the weak activity level. Spectropolarimetric observations of β Aql were carried out at CrAO over 51 nights from 1997 to 2015. The statistically significant magnetic field on β Aql have been detected in 24 out of 51 dates (Butkovskaya *et al.* 2017). The observed variability of the magnetic field lies in the range from -19.1 ± 1.1 G to 23.6 ± 1.0 G. The activity cycle of β Aql was found to be 969 ± 27 days, and the most probable rotation period was found to be $P_{\rm rot} = 5.08697 \pm 0.00031$ days.

Long time-series of the magnetic field measurements allows us to separate the large-scale and small-scale components of the magnetic field of β Aql (see Fig. 1). The large-scale component is due to the global large-scale magnetic field, whereas the small-scale component originates from the local magnetic activity probably due to emerging a leading spot's magnetic flux on the surface of the star. The manifestation of the small-scale magnetic activity on the surface of β Aql has been detected during 14 out of 51 nights.

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4. Summary

The long-term monitoring of the magnetic cycles is a key diagnostic in understanding how dynamo generation and amplification of magnetic fields occur in solar-like stars. The typical duration of the activity cycles in solar-like stars is up to several tens of years, the typical duration of the rotation periods is from several days to several tens of days. By analogy with the Sun, the magnetic fields of solar-like stars have the large-scale component and the small-scale component associated with the local manifestations of activity. To study the behavior of the magnetic field during the stellar activity cycles, long time-series of the magnetic field measurements covering these cycles are required. To study the manifestation of the local magnetic activity, long time-series of the magnetic field measurements covering several rotation periods are required.

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