DOI:http://dx.doi.org/10.18524/1810-4215.2020.33.216284

DETECTION OF EMERGENCE OF MAGNETIC FLUX TUBES IN THE PHOTOSPHERES OF DWARF 61 Cyg A, SUBGIANT β Aql AND GIANT β Gem

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ABSTRACT. Today, the study of stellar magnetic fields is one of the important research field in astrophysics because it provides us, in addition to physics, with information about space weather in the orbits of Earth-like planets in stars other than the Sun. Local magnetic fields on stars with convective envelopes are small-scale magnetic fields different in nature and structure from their global magnetic field. Unlike the Sun, through direct measurements we are able to measure only the magnetic field integrated over the visible disk of stars. However, we can register the magnetic field in the leading spot during the time interval when the corresponding magnetic flux tube already emerges on the surface of the star, and the magnetic flux tube of the following spot is still hidden in the interior under the photosphere. Our research is based on the spectropolarimetric observations carried out with 2.6m Shajn telescope equipped with the echelle spectrograph ESPL, CCD, and the Stokesmeter as a circular polarization analyzer. For measuring stellar magnetic fields the Single Line (SL) technique was developed at CrAO. This technique is based on the calculation of 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. Using SL technique emergence of large magnetic flux tubes at the surface of stars of V-IV-III luminosity classes (61 Cyg A, β Aql, β Gem) were first registered. We review the results of the study of local magnetic fields in these stars, including the results of modeling of magnetic field flux density and the size of their starspots. We also present the new results of spots modeling on β Aql. According to the considered geometric model, the rotational variability of the magnetic field and the extreme value of the field obtained from observations, we assume that the extreme radius of the spots at the surface of β Aql may exceed 9°.

Key words: stars, stellar magnetic activity, stellar magnetic fields.

АНОТАЦІЯ. Вивчення зоряних магнітних полів є одним із важливих напрямків астрофізики, оскільки воно надає нам інформацію не тільки про фізику зорі, але й про космічну погоду на орбітах землеподібних планет. Локальні магнітні поля у зірок з конвективними оболонками – це магнітні поля малого масштабу, що відрізняються за своєю природою та структурою від їх глобального магнітного поля. На відміну від Сонця, у зірок за допомогою прямих вимірювань ми можемо реєструвати лише магнітне поле, що інтегроване по видимому диску. Однак ми можемо реєструвати магнітне поле у головній плямі протягом часу, коли відповідна трубка магнітного потоку вже виходить на поверхню зірки, а трубка магнітного потоку хвостової плями все ще прихована у під фотосферою. Наші дослідження засновані на спектрополяриметричних спостереженнях, проведених за допомогою 2,6м телескопа ім. академіка Г.А.Шайна, оснащеного ешельним спектрографом ESPL, CCD та Стоксметром як аналізатором кругової поляризації. Для вимірювання зоряних магнітних полів в КрАО була розроблена методика Single Line. Ця методика заснована на розрахунку ефекту Зеемана в окремих спектральних лініях. Ключовою перевагою техніки Single Line перед іншими є здатність реєструвати локальні магнітні поля на поверхні зірок. За допомогою техніки Single Line вперше було зареєстровано появу великих трубок магнітного потоку на поверхні зірок V-IV-III класів світності (61 Cyg A, β Aql, β Gem). Ми розглядаємо результати моделювання магнітних плям на 61 Cyg A і β Gem та представляємо нові результати моделювання магнітних плям на β Aql. Відповідно до розглянутої геометричної моделі, змінності магнітного поля з періодом обертання зорі та граничного значення поля, отриманого в результаті спостережень, ми припускаємо, що максимальний радіус плям на поверхні β Aql може перевищувати 9°.

Ключові слова: зірки, магнітна активність зірок, магнітне поле зірок.

1. Introduction

Today, the study of stellar magnetic fields is one of the important research field in astrophysics because it provides us, in addition to physics, with information about space weather in the orbits of Earth-like planets for stars other than the Sun. Local magnetic fields in stars with convective envelopes are small-scale magnetic fields different in nature and structure from their global magnetic field. Local magnetic fields of different spatial scales are observed in the Sun. Solar local fields change at different time intervals from a few minutes to the 22-year Hale cycle. But, in contradiction to the Sun, the topology, evolution and variability of local and global magnetic fields of stars have not yet been studied in detail.

When active region is being formed on the surface of the Sun or a star, a magnetic flux tube of positive or negative sign first appears. The visible counterparts of magnetic flux tubes are solar or stellar spots. Sunspots usually appear in pairs of opposite magnetic polarities (leading and following sunspots). But magnetic flux tube of the opposite sign appears only after some time. Time delay between the appearance of the leading and following sunspots can reach a day. Unlike the Sun, through direct measurements we are able to measure only the magnetic field integrated over the visible disk of stars. This means that such direct measurements do not make it possible to estimate the local magnetic field in the spots if the active region has already formed on the surface of the star and contains spots of both polarities. However, we can register the magnetic field in the leading spot during the time interval when the corresponding magnetic flux tube already emerges on the surface of the star, and the magnetic flux tube of the following spot is still hidden in the interior under the photosphere. Observations of convective stars support this hypothesis. After emergence of the magnetic flux tube of the opposite sign, the opposite polarities cancel each other out and for given measurement accuracy we lose the ability to register the magnetic field of this active region.

A similar observational effect can be produced by a large unipolar spot. This interpretation can be accepted or rejected only if there are observations of the magnetic field in the next day. If in the next day the disk-integrated magnetic field returns to value expected at given rotation phase, this is evidence in favor of the emergence of magnetic flux tube. If in the next day (assuming the star is spinning slowly enough) the field remains anomalous, then, most likely, a unipolar spot has been registered. More detailed information can be obtained by comparing the theoretically modeled and observed Stokes profiles, or by measuring the magnetic field using sets of spectral lines, which formed mainly in the undisturbed photosphere and using another set of lines, which particularly formed in the spotted regions. It should be noted, on the Sun the probability of the formation of a unipolar spot is much less than the probability of the formation of a bipolar active region.

Performed at the CrAO observations allow us to assume that we registered the emergence of magnetic flux tubes of leading spots during the formation of the active regions in the stars of V-IV-III luminosity classes: 61 Cyg A (Sp K5 V, see Plachinda, 2004), β Aql (Sp G8 IV, see Butkovskaya et al., 2017), β Gem (Sp K0 IIIb, see Baklanova et al., 2011). Here, within the framework of this hypothesis, we discuss our earlier results of measuring the global and local magnetic fields of selected stars, as well as present new results of modeling the size and magnetic field of spots on β Aql.

2. Observational and diagnostic techniques for studing local magnetic fields

Since the 1980s, regular spectropolarimetric observations of nondegenerate stars of different spectral classes and evolution stages have been carrying out at the Crimean Astrophysical Observatory using the 2.6-m reflector named after academician Shajn (ZTSh). Today, for spectropolarimetric observations, the ESPL echelle spectrograph (Lagutin et al., 2019), the circular polarization analyzer (Stokesmeter) with a rotating input quarter-wave plate and a CCD detector ($2k \times 2k$) are used. The observations are carried out in the spectral range of 5000-6900 Å at the spectral resolution of $R \sim 51000$. To obtain the signal-to-noise ratio of ~250-450, the duration of an exposure is from 120 seconds for stars of magnitude $0.^{\mathrm{m}}0$ to 1800-3000 seconds for stars of 5^{m}-6^{m}.

The key difference between solar and stellar spectropolarimetric observations is that the last ones give Stokes profiles mean-weighted over star's visible hemisphere. In this case the significant cancellation of the signal from active regions of mixed polarity is observed. Therefore, unlike solar observations, the local magnetic fields on stars often remain unresolved. Semel et al. (1993) proposed a multi-line technique to add the polarization signal originating from several spectral lines into one pseudo profile, with an higher signal to noise. But, in general, the atmospheres of cool non-degenerated stars are characterized by a complex of physical conditions: spatial temperature and gravity inhomogeneities; gradients of temperature, microturbulence, density, velocity and stratification of chemical elements with depth; inhomogeneity of surface magnetic field (Plachinda et al. 2019). So, any multiline method, including the most popular Least Square Deconvolution (Donati et al., 1997), requires additional independent criteria for selecting spectral lines formed under the same physical conditions. Unlike multiline methods, we have developed and used Single Line method (SL-method), which calculates magnetic field using observed profiles of individual spectral lines (Plachinda & Tarasova, 1999; Plachinda, 2004; Butkovskaya & Plachinda, 2007; Plachinda, 2014) and is free from any model restriction.

3. Local magnetic fields of individual III-VI-V stars

Obtained at CrAO observational results allowed us to hypothesize that we have recorded the emergence of large magnetic flux tubes during the formation of an active region in stars of V-IV-III luminosity classes: 61 Cyg A (Sp K5 V), *β* Aql (Sp G8 IV), *β* Gem (Sp K0 IIIb) (Plachinda, 2004; Butkovskaya et al., 2017; Baklanova et al., 2011). Global and local magnetic fields of these stars folded with their axial rotation phases are illustrated in Figure 1.

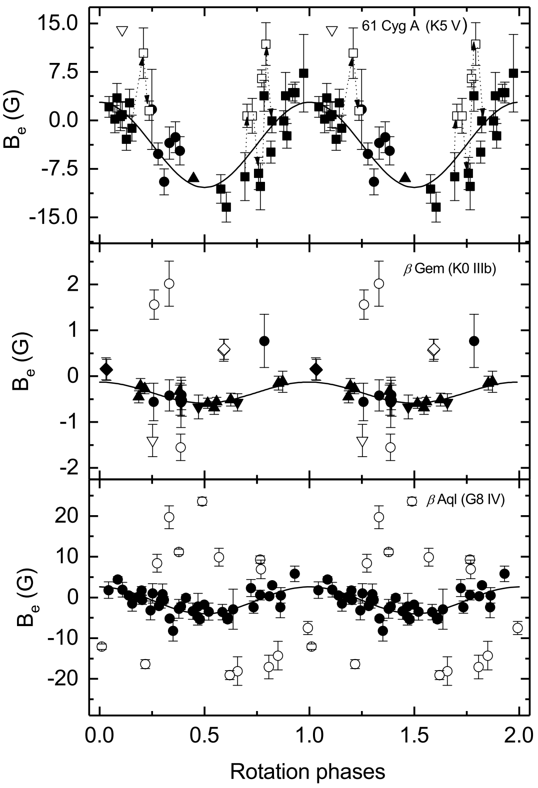

Figure 1: Global magnetic fields (filled symbols) and magnetic fields measured in dates when a strong spots contribution is supposed (opened symbols) of 61 Cyg A (*top panel*), *β* Gem (*middle panel*), *β* Aql (*bottom panel*) folded in phase with their axial rotational periods. The dipole fits are shown by solid lines. The arrows in the top panel connect the values of consecutive dates.

3.1. 61 Cyg A

Integrated over the visible hemisphere of 61 Cyg A (Sp K5 V, $P_{\rm rot} = 36.618 \pm 0.061$ days) magnetic field was estimated taking into account the contribution of spots of different sizes. Assuming the magnetic field of the spots is $B_{\rm spot} = 4000$ G, the simulated spot sizes for different initial parameters are 4.8° − 6.0°. In the top panel of Figure 1, open symbols marked values strongly out of the global magnetic field curve. Most likely, these outliers contain a significant contribution from the emerging magnetic flux tubes of active regions. For a more detailed description of data see Plachinda (2004). It should be noted that all outliers are of the same sign, as it should be during the same activity cycle. The arrows connect the values of consecutive dates. Thus, after almost a day, a lagging flux tube of an opposite sign compensates the magnetic flux of the tube that emerges first. This effect is well known from the physics of the Sun.

3.2. β Gem

Integrated over the visible surface of *β* Gem (Sp K0 IIIb, $P_{\rm rot} = 491.5$ days) magnetic field was estimated taking into account the contribution of spots of different sizes. Assuming the magnetic field of the spots is $B_{\rm spot} = 3000$ G, the simulated spot sizes for different initial parameters are $1.0° - 1.55°$. In the middle panel of Figure 1, open symbols marked values strongly out of the global magnetic field curve. As in the case of 61 Cyg A, these outliers, most likely, contain a significant contribution from the emerging magnetic flux tubes of active regions. For a more detailed description, see Baklanova et al. (2011). It should be noted that, unlike to 61 Cyg A, observations of *β* Gem overlap several activity cycles of the latter. As a result, the positive as well as negative outliers from the magnetic curve are registered.

Baklanova et al. (2011) additionally tested the hypothesis of the detection of the emergence of a large magnetic field tube on *β* Gem. Assuming the radiation transfer in magnetic field does not distort the geometry of the magnetic field, geometric modeling of the contribution of an unipolar spot to the magnetic field of the Sun as a star was performed. The emerging magnetic tube was simulated by a dipole of a conventional unipolar sunspot without penumbra. The spot was placed on the central meridian. The following parameters were used in the simulation: the coefficient of the linear law of darkening to the edge

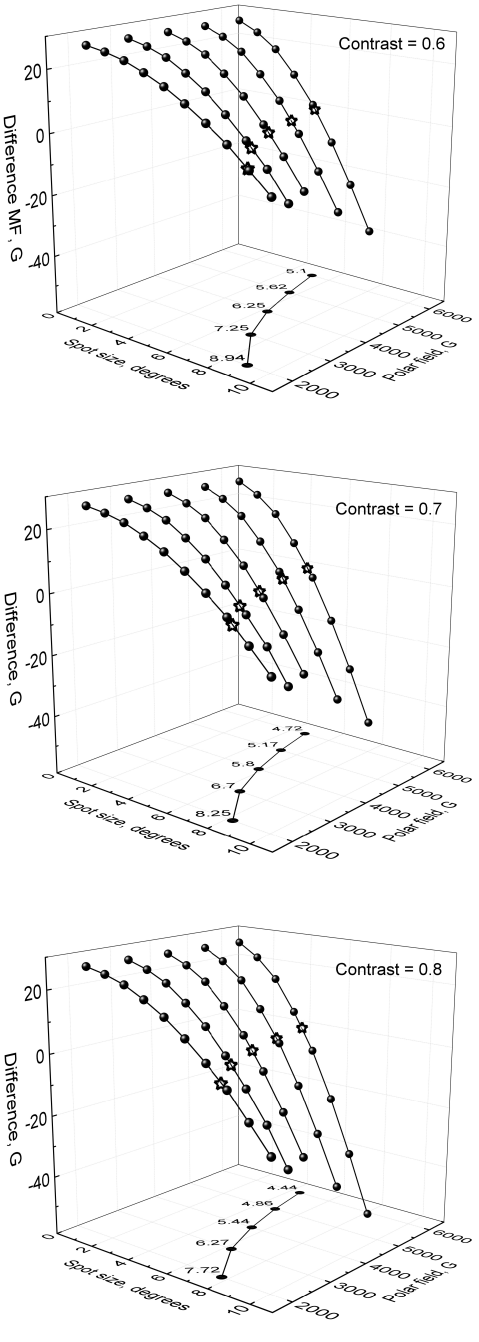

Figure 2: β Aql. For contrasts of the intensity in sunspot shadow to unperturbed photosphere equal to 0.6 (top panel), 0.7 (middle panel), and 0.8 (bottom panel), the dependencies of the discrepancy between calculated and measured longitudinal field component (Difference MF) on the spot radius (Spot size) and the field vector (Polar field) in the spot are presented. The asterisks mark points with minimal discrepancies between the observed and calculated magnetic field. Projections of these best fitted values on the lower plane Spot radius − Spot field are shown with indication of spot radius.

$u = 0.55$, the angle between the axis of rotation and the line of sight $i = 90°$, the spot latitude $\phi = 30°$, the ratio of the radiation intensity in the spot shadow to the unperturbed photosphere $\gamma = 0.4$, the tube radius $r = 1.5°$, the magnetic field in the tube $B_{\rm tube} = 4000$ G. The contribution of the magnetic flux tube to the global magnetic field of the Sun as a star was found to be only 1 G, this is in good agreement with the solar data. This geometric approach makes it possible to obtain a family of solutions that provides information on the radii of floating flux tubes and their magnetic fluxes.

3.3. β Aql

For β Aql (Sp G8 IV-V, $P_{\rm rot} \sim 5.1$ days), all observations presented in the bottom panel of Figure 1 were obtained at the CrAO (Butkovskaya et al., 2017). As for the two previous stars, open symbols represent the magnetic field on dates, where, apparently, a significant contribution is made by the small-scale magnetic field associated with the emergence of the forming active regions.

In this work, for the date 2014 October 06, when strongly deviated magnetic field $B_{\rm e} = 23.6 \pm 1.0$ G was registered, we modeled the possible sizes of magnetic spots for different magnetic fields in the spots (see Table 1 and Figure 2). The following parameters were used in the simulation: the coefficient of the linear law of darkening to the edge $u = 0.583$, the angle between the axis of rotation and the line of sight $i = 25°$ (Butkovskaya et al. 2017), the latitude of the spot $\phi = 40°$, the spot radius from 1° to 10°, magnetic field in spot from 2000 to 6000 G. The simulated spot was placed on the central meridian. With these parameters, the differences between the observed value of the longitudinal field $B_{\rm e} = 23.6$ G and that simulated for the visible hemisphere with a spot were calculated. It should be noted that the radius of β Aql is $3.2R_{\odot}$, so the gas pressure in the atmosphere of β Aql is less than the gas pressure in the solar atmosphere. Therefore, to maintain the configuration of the magnetic field tube in atmoshere of β Aql, a smaller magnetic flux is sufficient. Therefore, we used a contrast value of $0.6 - 0.8$, which is lower than that of the Sun.

According to B*ü*nte & Saar (1993), for stars with temperatures and luminosities similar to β Aql, the typical magnetic field of spots range from 1800 to 3300 G. According to the top panel of Figure 2, this range of the magnetic field corresponds to the range of spot radii from 9° to 7.5°. With decreasing contrast (for the Sun ∼0.3-0.4 in spot shadow), the radius of the magnetic flux tube (i.e. the radius of the spot) increases. According to the considered geometric model, the rotational variability of the magnetic field and the extreme value of the field obtained from observations, we assume that the extreme radius of

Table 1: Simulated sizes of magnetic spots (second column) for different magnetic fields in the spots (first column). Here spot sizes best fitted to $B_e = 23.6$ observed at 2014 October 06. The differences between observed B_e and calculated B_{calc} magnetic fields are presented in column 3.

B_{spot}, G	Spot size, °	$B_e - B_{calc}$, G
	Contrast = 0.6	
2000	8.9	0.06
3000	7.3	0.13
4000	6.3	0.15
5000	5.6	-0.08
6000	5.1	-0.04
	Contrast = 0.7	
2000	8.3	0.11
3000	6.7	-0.01
4000	5.8	-0.01
5000	5.2	-0.02
6000	4.7	-0.04
	Contrast = 0.8	
2000	7.7	-0.08
3000	6.3	-0.10
4000	5.4	-0.02
5000	4.9	-0.01
6000	4.4	-0.07

the spots at the surface of β Aql may exceed 9° (1/40 of the circle). The radii of large solar spots at the same latitude are $\sim 1.5°$. For such radii of spots on β Aql the magnetic field become abnormally big: $B_{spot} \sim 20000$ G. Thus, our geometric modeling allows us to conclude that the big spots at the surface of β Aql are several times larger than big sunspots.

4. Conclusions

In this paper we discuss the possibility of detection of activity regions by direct measurements of magnetic field in stars with convective envelopes. We present our results of registration of emergence of large magnetic flux tubes during the formation of an active region in selected stars of V-IV-III luminosity classes: 61 Cyg A (Sp K5 V), β Aql (Sp G8 IV), β Gem (Sp K0 IIIb). We also present the new results of modeling the size and magnetic field spots on β Aql. According to the considered geometric model, the rotational variability of the magnetic field and the extreme value of the field obtained from observations, we assume that the extreme radius of the spots on the surface of β Aql may exceed 9° (1/40 of the circle).

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