DIRECT MEASUREMENTS OF THE GENERAL MAGNETIC FIELD ON THE SOLAR-LIKE STARS

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ABSTRACT. We report the high-precision spectropolarimetric measurements of the general magnetic field (GMF) on a solar-like star 61 Cyg A. The magnetic field shows periodic variations due to stellar rotation with a period of $P_{mf} = 36.59 \pm 0.18$ days. The net longitudinal magnetic field of 61 Cyg A varied from -13 G to + 4 G. The conclusion was made that the non-axisymmetric large-scale magnetic field (original magnetic field - OMF) on the surface of the Sun and solar-like stars ξ Boo A and 61 Cyg A is present in addition to toroidal and axisymmetric poloidal fields, which are produced by dynamo. The characteristics of the OMF point to a presence of a global magnetic field in the star radiative interior and reflect internal field properties on the surface. The birth and formation of magnetic active regions (ARs) on the surface of the solar-like star 61 Cyg A has been registered. The numerical simulations were compared with magnetic measurements, and lead us to the conclusion about the presence on 61 Cyg A of more strong magnetic fluxes of ARs ($\sim 10^{23} - 10^{24}$ Mx) than on the Sun. These ARs can be formed at the same latitudes as on the Sun.

Key words: Stars: late-type; stars: individual: 61 Cyg A, ξ Boo A, Sun; stars: magnetic fields.

1. Introduction

1.1. SUN

The Sun is the only star for which detailed observations with very high spatial and temporal resolution are available. The general magnetic field on the Sun, seen as a star (GMFS), is the surface-averaged value of the longitudinal component of small- and large-scale magnetic structures (Severny 1969; Scherrer et al. 1977; Kotov et al. 1998). Small-scale magnetic structures are one manifestation of the large-scale, organized magnetic field on the Sun.

As we believed, there are two main components of the large-scale magnetic field on the Sun in terms of standard α-ω dynamo:

1). The magnetic field at the base of the convection zone of approximately toroidal geometry with a field strength in the range (3-10)$\times 10^4$ G and manifests itself when magnetic loops emerge on the surface in bipolar active regions. The latitude distribution of the toroidal field is mirrored by the observed active latitudes. In the northern and southern hemispheres of the Sun the directions of the azimuthal field components are reversed and the direction of these fields changes cyclically with a period of about 22 yr.

2). The second component of the large-scale field is an axisymmetric poloidal field (essentially a dipole) that also changes its polarity with a period of about 22 yr. The poloidal dipole reaches peak values of about 2-3 G on the surface of the Sun during minima of spot activity (see, for example, Zhang, Zirin, and Marquette 1997).

Variability of the GMFS with the synodic rotation period of 26.92 days is shown in Figure 1 (see Plachinda and Tarasova 2000). The average daily values of the GMFS from 1968 to 1997 (N = 10838 measurements) were kindly provided by Kotov V.A. and Haneychuk V.I. (1999, private communication). Results of GMFS observations obtained at three observatories (Crimean Astrophysical Observatory, 1968 – 1976; Mount Wilson Observatory, 1970 – 1982; Wilcox Solar Observatory of the Center for Space Science and Astrophysics of Stanford University, 1975 – 1997) were used as the basic data. The full rotation period is plotted twice on the X-axis. Filled circles are measured data binned into 16 bins, and error bars are rms errors above the binned means. One can see that during 29 years of observation of GMF of the Sun as a star, the excess of the positive magnetic flux dominated on one side of the Sun, the excess of the negative flux dominated on the opposite side, and GMFS does not reverse its polarity with the 22 yr solar cycle period.

1.2. ξ Boo

The first observational study of the general magnetic field (GMF) as a function of rotation on a solar-like star other than the Sun was carried out for ξ Boo A (Sp G8 V) by Plachinda and Tarasova (2000). The magnetic field variations on ξ Boo A phased with the rotation period of 6.1455 days are represented in Figure 2 (see Plachinda and Tarasova 2000). Magnetic field measurements are in gauss and the total period is shown twice. The "X" shows the single measurement by Brown and Landstreet (1981), obtained with multislit magnetometer. Measurements obtained by Borra et al. (1984) using the multislit magnetometer are shown by filled triangles and by small open triangles as well. Measurements obtained with Stokesmeter by Hubrig et al. (1994) are shown by filled circles and by small open circles. Results of observations presented by Plachinda and Tarasova (2000) are shown by filled squares. Small open circles and triangles represent data that lie out of the supposed curve of magnetic field variations with rotational period. Bars are mean values of rms errors of every type of measurements. The GMF of the ξ Boo A varies from -10 G up to +30 G as a function of stellar rotation phase and the phase of the polarities has remained constant for about 16 yr. ξ Boo A is more young and more active solar-like dwarf than the Sun with variability of the Ca II emission but without clearly expressed solar-like periodicity of the activity (Baliunas et al. 1995).

1.3. 61 Cyg A

Cyg A were made at the Crimean Astrophysical Observatory and at the McDonald Observatory. This star has the same level of activity as the Sun and clearly expressed solar-like Ca II emission periodicity 7.3 yr (Baliunas et al. 1995). We find significant power in the magnetic field variations with a period equal to $P_{mf} = 36.59 \pm 0.18$ days. The rotational period P_{mf}, which determined using magnetic field measurements is smaller than the rotational period P_s determined using the variability of Ca II H and K line index S both for ξ Boo A ($P_s = 6.2$ and $P_{mf} = 6.1455$ days) and 61 Cyg A ($P_s = 37.9$ and $P_{mf} = 36.59$ days). Furthermore, for ξ Boo A Toner and Gray (1988) determined the period of 6.45 days from the variations in line asymmetries and temperature. We supposed that observed discrepancy in the values of the rotational periods for ξ Boo A and 61 Cyg A can be caused by differential rotation of these stars. The magnetic field variations on 61 Cyg A phased with the rotation period are represented in Figure 3. Magnetic field measurements are in gauss and the total period is shown twice. Phases are calculated with a zero epoch at the positive extremum of the magnetic field: $HJD_{(max)}$ = 2,450,989.20 + 36.59 ± 0.18, where HJD is the Julian Date in the heliocentric coordinate system. Measurements obtained using 2.6-m Shajn telescope are shown by filled and open circles, and measurements obtained using 2.7-m Harlan J. Smith telescope are shown by filled and open squares. The filled down triangle shows the single measurement by Borra et al. (1984), obtained with multislit magnetometer. Single measurement obtained by Brown and Landstreet (1981) using the multislit magnetometer is shown by open up triangle. The measurements, which lie out of the fitting curve more than 3 σ were single out by open signs. If deviations of the measurements from a curve in following night or in one-two nights exceeded 2 σ they also were designated by open symbols. Dashed arrows connect progression of the observations in time for lie out points. The solid curve was obtained by least squares fitting numerical simulations for the filled signs. We used magnetic configuration that was produced by two centered magnetic dipoles: the axis of the first dipole coincides with rotation axis of the star (axisymmetric dipole) and axis of the second dipole lies in the plane of rotation equator of the star (nonaxisymmetric dipole). We do not know geometrical structure of a global magnetic field of this star therefore the values of both formal magnetic churches of the dipoles were taken equal each other (by analogy to the Sun, where magnitudes of the axisymmetric dipole and general magnetic field of the Sun as a star are close on values and varies in the range 0.2 - 3 G). For the case of such approximation conditions there is a unique solution for the angle between the rotation axis and the line of sight, $i = 52^o$, and for the polar strength of the field of both dipoles, $B_p = \pm$ 34 G. The error in standard deviation of the magnetic field measurements (filled signs) concerning the fitting curve σ = 1.9 G. The best fitting curve in the case of modeling by one dipole is practically coincides with the found curve for two dipoles, but in the latter case $i = 33^o$, $B_p = \pm$ 60 G and $\sigma = 1.9$ G.

These abovementioned high-precision spectropolarimetric measurements open up the question: *Whether GMF contains the third large-scale component of the common magnetic field on the Sun and solar-like stars or it is the surface-averaged value of the longitudinal component produced by presence of the toroidal and axisymmetric fields only?* In particularly, Plachinda and Tarasova (2000) hypothesized that the GMF is observed as a bicomponent magnetic field composed of a large-scale axisymmetric magnetic field and a large-scale nonaxisymmetric magnetic field. A possible contribution to the GMF by strong local magnetic fields (manifestation on the star surface of the toroidal large-scale component) similar to solar active regions was not considered, because authors assumed the mutual cancellation of opposite polarities typically found in active regions.

2. General Magnetic Field

According to theoretical researches executed by Mestel (1967), Alfven (1981), Rudiger and Kitchatinov (1977), Gough and McIntyre (1998), MacGregor and Charbonneau (1999), Schussler (1975), Parker (1981), Dudorov et al. (1989), and Kitchatinov, Jardine, and Cameron (2001) we can build following scenario:

1) a magnetic flux (primordial magnetic field) is captured from a protostellar cloud by the forming star;

2) pre-main sequence rotating fully convective star (Hayashi-phase) can drive hydromagnetic dynamos;

3) the dynamo-generating field is incorporating into the growing radiative core;

4) magnetic field of the radiative core is largest for an orientation normal to the rotation axis of the star (nonaxisymmetric field); 5) Gough and McIntyre (1998): "...it seems unlikely that the rapidly oscillating field associated with the solar cycle would contribute significantly to the dynamics in the radiative zone, particularly in view of the 10^6 yr tachocline ventilation time" (stability of the internal magnetic field).

On the other hand, today we have measurements of the GMF for three solar-like star: Sun (observations average about 30 yr), ξ Boo A (observations average about 16 yr), and 61 Cyg A (observations average 2 yr). In all three cases nonaxisymmetric large-scale component of the field is present. For the Sun the reverse of the nonaxisymmetric field sign with activity cycle is absent. For ξ Boo A phases of GMF field variability also remained to be a constant without the reverse of the sign in contradiction to a non-periodic long-time variability of the Ca II emission. These coincidences on the one hand of abovementioned theoretical conclusions of different authors as well as results of their numerical simulations and on the other hand the observed data (the presence of the nonaxisymmetric large-scale field component and the absence of the sign reverse with periodicity of the activity (Sun) or with non-periodic time of the activity (ξ Boo A) allows us to make the assumption that the nonaxisymmetric large-scale component of GMF is really present and its characteristics point to a presence of a global magnetic field in the solar-like radiative interior and reflect internal field properties on the surface as well. We define the nonaxisymmetric large-scale component of GMF as the "origin magnetic field" (OMF), meaning that this field point to a presence of a global magnetic field in the solar-like star's radiative interior beneath the tachocline, reflect its properties on the surface of the star, and this field can be initial magnetic field for hydromagnetic dynamo of solar-like stars. If nonaxisymmetric field is really a large-scale component then it is necessary for taking into account OMF both at modelling a dynamo and at an explanation of phenomena of activity. Kitchatinov, Jardine and Cameron (2001) assume that the presence of the nonaxisymmetric field rooted in the core may be the reason why the solar activity statistics lack axial symmetry. Besides, a superposition of the nonaxisymmetric field of internal origin with the toroidal field of the axisymmetric dynamo makes an enhanced field on the longitude region where both fields coincide in sign and it makes a decreased field where both ones have opposite signs (phenomenon of the active longitudes observed in solar and stellar activity (in the last case see Berdyugina and Tuominen (1998) and Korhonen et al. (1999)). Also the observed alteration of high and low activity cycles on the Sun is explained in terms of a weak internal magnetic field (Pudovkin and Benevolenskaya 1984).

3. Local Active Regions on the Surface of the 61 Cyg A

The greatest duration of observable magnetic disbalance on 61 Cyg A (see Figure 3) is only four days, while the period of rotation $P_{rot} = 36.59 \pm 0.18$ days. What is nature of these events? We have rejected the hypothesis of short-time variations of the GMF because we have not found real arguments for the benefit of such assumption. After numerical simulations, using the spots of the round form with dipole geometry of the magnetic field, we have rejected also the hypothesis about unipolar very big spot, which crossing the visible hemisphere of the star near the limb. It is not possible to approximate the observed behaviour of the longitudinal field component without rapid changing in time of dipole parameters. Additionally, the strength of such spot field must be 60,000-70,000 G. It not seems real, because for more active M dwarfs Saar and Linsky (1985), Saar (1994), and Jochns-Krull and Valenti (1996) detected spot magnetic fields not exceeding 5 kG. Furthermore, Savanov and Savelyeva (1996) using Stenflo-Lindergen method detected spot magnetic fields for 61 Cyg A $B_f = 1300 \pm 250$ G, but f, filling factor, is unknown value.

Owing to the above we have assumed the following. Open circles and squares indicate the process of emergence in the atmosphere of a first "preceding" part of the active region (complex of the magnetic flux tubes of one sign), and after that, with a time lag, a second "following" part of the active region with opposite sign of flux that compensates registered disbalance of the observed magnetic field emerge on the surface. In other words, it is supposed that the birth (stage of the disbalance growth) and formation (stage of the disbalance compensation) of magnetic active regions on the surface of the solar-like star 61 Cyg A has been registered. It do not seems impossible that the occurrence on the surface of one magnetic polarity outstrip another, and, in result, a balance of total magnetic flux on the surface can be broken for a short time. As we know for the Sun, first manifestation of a new bipolar active region in the solar atmosphere is the appearance of a small, compact and bright bipolar plages (Sheeley 1969). In different terms, an emerging flux region is caused by the emergence of the top of a loop bundle, shaped as a peaked arch, consisting of many magnetic flux tubes. It is meaning that areas of strong magnetic field of one sign are paired with strong, adjacent fields of the opposite sign during first manifestation of magnetic flux of new active region (AR) on the surface. In this case we can not register the disbalance of the magnetic flux because occur the mutual cancellation of opposite polarities, and therefore the GMF is registered only. What is necessary for receiving the observed short-time magnetic disbalance? One can supposed follow most simple scenario: 1) the rising magnetic loop (as complex of the magnetic flux tubes) must be broken off by motions of the matter and after that 2) the passage outside on a surface both arms of the magnetic loop with opposite signs should not be synchronous. Owing to the above the magnetohydrodynamic computation of the process of the magnetic flux tubes capture and avulsion by convective motions of the matter, as well as more detailed observations, are needed to build an actual picture of the observed disbalance events on the 61 Cyg A.

What parameters of AR on the surface of the 61 Cyg A are necessary to describe observed events of the disbalance? One can see there is no unambiguous solution because excessive number of free parameters: coordinates, magnetic flux, and size of area. Therefore the question needs to be restated: Whether there are solutions which would be relative to parameters (flux, size, and latitude) of ARs on the Sun? Such type question based on the general ideas today about analogies of processes of activity on the Sun and late-type stars, because we have a wealth of evidences for such analogies. Alekseev and Gershberg (1997) have successfully applied models of a zonal spottedness of G - K - M dwarfs in order to study the photometric rotational variability of these stars. The our numerical simulations were compared with magnetic measurements, and lead us to the conclusion about the presence on 61 Cyg A of more strong magnetic fluxes of ARs ($\sim 10^{23} - 10^{24}$ Mx) than on the Sun ($\sim 5 \times 10^{22}$ Mx). These ARs can be formed at the same latitudes as on the Sun.

4. Summary

1) The magnetic field on a solar-like star 61 Cyg A shows periodic variations due to stellar rotation with a period of 36.59 days and varies from - 13 G to + 4 G.

2) The supposition that observed discrepancy in the values of the rotational periods for ξ Boo A and 61 Cyg A can be caused by differential rotation of these stars was made.

3) The conclusion was made that the nonaxisymmetric large-scale component on the surface of the Sun and solar-like stars ξ Boo A, and 61 Cyg A is present, in addition to toroidal and axisymmetric poloidal fields, which produced by dynamo. The characteristics of the OMF point to a presence of a global magnetic field in the stars radiative interior and reflect internal field properties on the surface.

4) The birth (stage of the magnetic disbalance growth) and formation (stage of the magnetic disbalance compensation) of magnetic active regions on the surface of the solar-like star 61 Cyg A has been registered. The occurrence on the surface of one magnetic polarity outstrips another, and, in result, a balance of total magnetic flux on the surface is broken for a time of the AR formation.

5) The conclusion about the opportunity of the presence on 61 Cyg A of more strong magnetic fluxes of active regions ($\sim 10^{23} - 10^{24}$ Mx) than on the Sun ($\sim 5 \times 10^{22}$ Mx), which can be formed at the same latitudes as on the Sun, was made.

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