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ОБСЕРВАТОРИИ

Global magnetic field of the Sun as a star and of convective stars

The report is dedicated to Andrew Severny memory

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Abstract. In terms of the Babcock' and Leighton' phenomenological magneto-kinematic model of the solar cycle and in terms of standard α-Ω dynamo theory, there are only two main 0 components of large-scale magnetic field on the Sun: toroidal magnetic field and poloidal field. The first results of the magnetic field measurements of the Sun as a star were published by A. Severny, and named as General Magnetic Field (GMF) of the Sun as a Star. What is the origin of the GMF?

Using frequencies for $P_1 = 26.929 \pm 0.015$ d and $P_2 = 27.144 \pm 0.015$ d, we can obtain main periods in the power spectrum for GMF of the Sun as a star including period of activity cycle. One of the initial periods is due to a rigid rotation of radiative zone, and the second one is produced by differential rotation of the Sun's top layer. The Origin Magnetic Field of the Sun's radiative zone is captured by moving matter and transported up to the surface, where a beating of two main frequencies produces observing picture.

The presence of weak general magnetic field (up to some dozen Gausses) for 21 convective stars (F9-M3 spectral types and I-V luminosity classes) is detected nowadays. For two solar-like stars variations of the GMF as a function of the stellar rotation has been determined: for more active and more young star than the Sun ξ Boo A (G8 V) with $P_{rot} = 6.198$ d, and for old solar-like star 61 Cyg A (K5 V) with $P_{rot} = 36.617$ d. For ξ Boo A GMF variations as a function of rotational period was confirmed using MuSiCoS Stokesmeter in 2003. The Crimea curve (1990-1999) shows domination of the dipole component contrary to the MuSiCoS curve for 2003 year, which demonstrates the presence of quadrupole component. An existence of the GMF on convective stars with vigorous convective envelopes confirms a hypothesis that the GMF is a real phenomenon.

GMF reflects properties of a stationary global magnetic field of the Sun's (convective star's) radiative interior on its surface, and there appears to be the third large-scale component of the magnetic field.

Key words: stars: convective stars: Sun; solar-like stars; sub-giants; giants; supergiants; magnetic field; activity

1 Introduction

Investigations of solar activity have shown that almost all manifestations of solar activity (chromospheres and coronae, plages and spots, flares, etc.) are related to magnetic fields. Why do we study global magnetic fields on the Sun and on other convective stars? The study of large-scale magnetic fields allows us to reveal:

a) the main processes causing the activity of a star as a whole; b) dependence the activity on stellar angular momentum (because stellar rotation puts its energy to regeneration of magnetic fields by dynamo mechanisms, and owing to stellar rotation, magnetic field transports energy of angular momentum into circumstellar environment); c) connection of the solar neutrino flux variability with rotation of the internal global magnetic field.

The first results of the magnetic field measurements of the Sun as a star were published by A. Severny (1969) in the Nature. It is the General Magnetic Field of the Sun as a Star (GMFSS). The General Magnetic Field (GMF) is a surface-averaged value of the longitudinal component of magnetic structures. Observations of the Sun's GMF were obtained mainly at four observatories: Crimean Astrophysical Observatory (Crimea), 1968-present; Mount Wilson Observatory (USA), 1970-1982; Wilcox Solar Observatory of Stanford University (USA), 1975-present (see Solar Geophysical Data); and the Sayan Observatory (Russia), 1982-present.

In terms of Babcock' and Leighton' phenomenological magneto-kinematic model of the solar cycle (Babcock, 1961; Leighton, 1964; Leighton, 1969) and in terms of standard α-Ω dynamo theory, there are only two main axisymmetric components of large-scale magnetic field on the Sun: toroidal magnetic field and poloidal field. Both toroidal (strong) and poloidal (weak) fields change its polarity with a period of $\sim$22 ys. Toroidal magnetic field lies in the base of the convective zone and manifests itself when magnetic loops emerge on the surface in bipolar active regions, reaching peak values during maximum of spot activity. The poloidal field lies under the photosphere and changes its polarity with a period of $\sim$22 yr as well, but reaching peak values of about 1-2 G on rotation poles during minimum of spot activity. It is believed today that the underlying cause of the solar activity cycle is the interplay between poloidal magnetic field, differential rotation, and convection that is illustrated by the most developed Babcock' and Leighton' phenomenological model of the solar cycle. According to aforesaid, what is the origin of the GMF?

2 Discussion

Because the GMF as a phenomenon is absent in the Babcock' and Leighton' phenomenological magneto-kinematic model of the solar cycle and GMF is absent in terms of standard α-Ω dynamo theory also, therefore, the first point of view on the origin of the GMFSS: "...we measure magnetic disequilibrium of the Sun" (Haneychuk et al., 2003).

In spite of this viewpoint, the following general properties of GMFSS are derived: GMF strength versus the synodic rotational period (P_{rot} = 26.93 days) shows both sign and shape variations. This period has not varied over the three decades with a half of direct measurements. Using information about measurements of the interplanetary magnetic field, P_{rot} has not varied over the about eight decades time span (Haneychuk et al., 2003). Both dipole, as dominant, and quadrupole components of the field are detected in the observations (see Solar Geophysical Data). The amplitude of variations of the GMF varies with the period of sunspots cycle: the GMF is strongest during peak in spot activity, reaching values of about 1 - 2 G. During of time span of direct observations, positive magnetic flux excess as a whole is concentrated on the one side of the Sun, and negative flux excess is concentrated on the opposite side (see Figure 4 in Haneychuk et al., 2003), therefore we cannot claim that the GMF of the Sun reverses its polarity with the 22 yr solar cycle period. The ratio of the positive to negative magnetic flux $\Phi_+/\Phi_- = 0.99$ (Plachinda and Tarasova, 2000).

Owing to described above properties of GMF, especially because there is balance of positive and negative magnetic fluxes, $\Phi_+/\Phi_- = 0.99$, in agreement with Maxwell equation $\nabla \bullet \mathbf{B} = 0$ (the tubes of the induction $\mathbf{B}$ are closed), we hypothesize that the GMF is a real nonaxisymmetric large-scale field of the Sun. Therefore the disequilibrium of the magnetic field on the Sun is absent as well as Dirac' magnetic monopoles which we need to produce this disequilibrium.

The gas in the convective outer layers of the Sun rotates faster at the equator than at the poles, and gas rotates almost uniformly in the radiative zone. This structure (including the presence of the tachocline zone) has been measured seismologically. Gough and McIntyre (1998) argue that we must have a magnetic field in the radiative interior in order to explain the uniform rotation of the radiative zone. Such an internal field of the Sun also is required in the magnetic models of Rudiger and Kitchatinov (1997) and MacGregor and Charbonneau (1999). As we know, the magnetic flux (primordial magnetic field) can be captured from a protostellar cloud by the forming star. The star then evolves through a fully-convective Hayashi-phase. Direct observations of magnetic fields (Johns-Krull et al., 1999a; Johns-Krull et al., 1999b) and magnetic activity (e.g., Basri et al., 1992) of T Tauri stars support the hypothesis that rotating pre-main-sequence convective stars can drive hydromagnetic dynamos. This dynamo-generating field can be incorporated into the growing radiative core (Parker, 1981; Dudorov et al., 1989). Kitchatinov et al. (2001) also argued that contemporary magnetic fields in radiative cores of solar-like stars are relics of hydromagnetic dynamous operating over the pre-main-sequence epoch when a core was being formed. Their numerical simulations show that this internal field is largest for an orientation normal to the rotation axis of the star. The GMF in the Sun's radiative interior beneath the tachocline must be stationary (Gough and McIntyre, 1998). The hypothesis about the effect of quasistationary primary field of the Sun on the behaviour of solar activity and background magnetic field during the 22-year solar cycle has been discussed by different authors (see Pudovkin and Benevolenskaya, 1984; Levy, 1992; Levy and Boyer, 1982; Boyer and Levy, 1984; Benevolenskaya and Pudovkin, 1985).

The value of the GMF varies with the period of sunspots cycle: maximal solar activity – maximal GMF amplitude; minimal solar activity - minimal GMF amplitude (Kotov et al., 1998). This picture represents, to first order, a beating of two main neighbour frequencies, 1/26.93 and 1/27.14, which are produced by differential rotation of latitude belts with most contribution to the registered signal (equatorial and active region areas of the Sun).

Using only two frequencies for $P_1 = 26.929 \pm 0.015$ d and $P_2 = 27.144 \pm 0.015$ d we can obtain main periods in the power spectrum for GMF of the Sun as a star including period of activity cycle. One of the initial periods is due to a rigid rotation of radiative zone, and the second one is produced by differential rotation of the Sun's top layer (Plachinda, 2004b). Hence, we can hypothesize that Origin Magnetic Field of the Sun radiative zone is captured by moving matter and transported to the surface, where beating of two main frequencies produces observing GMF picture of the Sun as a star because a superposition is one of the main property of the magnetic field. As a rule, possible contributions to the GMF by strong local magnetic fields similar to solar active regions (toroidal field) is small because the mutual cancellation of opposite polarities typically are found in active regions. The expected contribution to the GMF from the net longitudinal component of the solar north and south polar fields is a long term drift with approximately an annual period, but this variation is negligible when averaging by years. The main question before this hypothesis is what should be mechanism of macro-organizing of the magnetic fields which are captured by moving matter and transported to the surface? Such possibility gives us the law of parameter correlations of self-organizing structures of the open thermodynamic system. Gershberg wrote (2005): "In the thermodynamics of open systems, a star as a whole is a dissipative system of the greatest scale, in which global magnetic fields are self-organized due to the energy of rotation and convective motions (Gershberg, 1986), while dissipative systems are realized in small-scale structures due to the energy of the carrier of the deficit of photospheric radiation resulting in stellar flares and other local phenomena. Probably, this general synergetic approach will give a key to understanding the various manifestations of the solar-type activity on main-sequence stars."

The intricate and time-dependent magnetic structure that is directly observed in the solar atmosphere is attributed to the interaction of magnetic field, convection, and rotation in the solar envelope. This phenomenon is not expected to be unique to the Sun, and that is inferred to be present in other late-type stars with vigorous convection in the envelope below the atmosphere. Therefore we can expect the presence of the GMF in the radiative interior of these stars and penetration of it into the surface, where the origin magnetic field becomes the initial magnetic field for regenerating magnetic fields by different mechanisms. There is a wealth of indirect evidence for the presence of magnetic field on late-type stars of all luminosity classes: spots, flares, chromospheres, transition regions, coronae, winds, etc. Currently, we have direct spectroscopic data indicating locally strong magnetic field (1000-4000 G) on the surface of main-sequence stars of F-G-K-M spectral classes (see, for example, Rueedi et al., 1997; Johns-Krull and Valenti, 1996) and the existence of strong local magnetic fields on the surfaces of rapidly rotating RS CVn stars (K0 dwarfs AB Doradus and LQ Hydrae, and K1 subgiant HR 1099 (V711 Tauri)) which were determined using the spectropolarimetric technique of Zeeman-Doppler imaging (Donati et al., 2003).

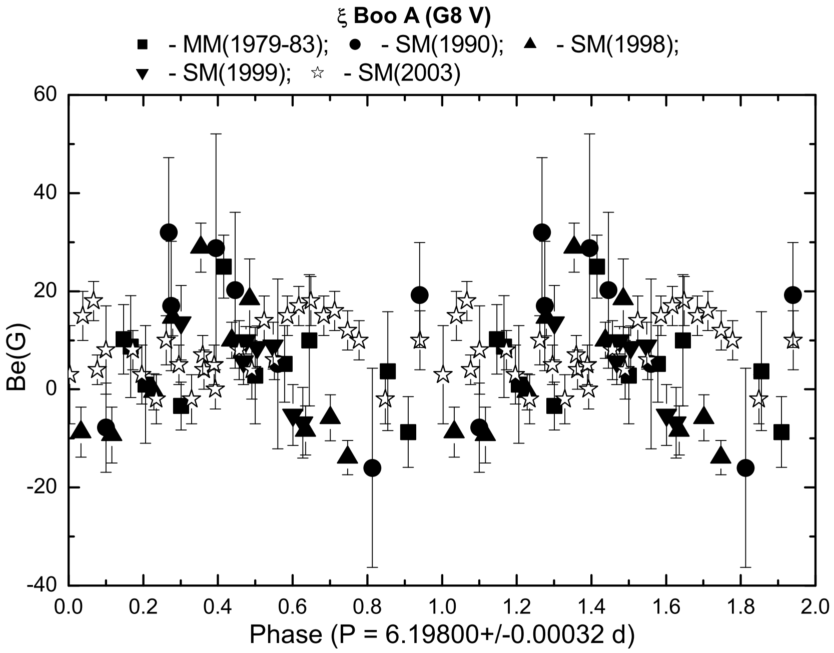

Fig. 1.

The program of systematic measurements of GMF on slowly rotating stars with convective envelopes was initiated at Crimea in 1989. The observations and data reduction were carried out using 2.6m Shajn telescope, Stokesmeter, coude spectrograph and "Flip-Flop" Zeeman Measurements technique (Plachinda et al., 1993; Plachinda & Tarasova, 1999; Plachinda, 2004a; Plachinda, 2005).

Today, the presence of weak general magnetic field (up to some dozen Gausses) for 21 convective stars (F9-M3 spectral types and I-V luminosity classes) is detected (Plachinda, 2004a). For two solar-like stars variations of the GMF as a function of the stellar rotation has been determined: for more active and more young star than the Sun ξ Boo A (G8 V) with $P_{rot} = 6.198$ d, and for old solar-like star 61 Cyg A (K5 V) with $P_{rot} = 36.617$ d. For ξ Boo A GMF variations as a function of rotational period was confirmed using MuSiCoS Stokesmeter 2003 by Petit et al. (2005) (see Fig. 1, where GMF variations are shown as a function of rotational period: SM - Stokesmeter (Crimea, 1990; 1998-1999 and MuSiCoS Pic du Midi, 2003); MM - Multislit magnetometer (Brown and Landstreet, 1981; Borra et al., 1984)). The Crimea curve (1990; 1998-1999) shows domination of the dipole component contrary to the curve for 2003 year, which demonstrates the presence of quadrupole component. Analogue behaviour of the GMF on the Sun is present. An existence of the GMF on convective stars with vigorous convective envelopes confirms a hypothesis that the GMF is a real phenomenon.

3 Conclusion

GMF reflects properties of a stationary global magnetic field of the Sun's (convective star's) radiative interior on its surface, and there appears to be a third large-scale component of the magnetic field.

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