The Evolution of Cyclic Activity of the Sun in the Context of Physical Processes on Late-Type Stars

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Abstract Features of the solar cycle in the context of stellar activity are investigated. We discovered reliably differential rotation in chromospheres of some stars and presented the first stellar butterfly diagrams. These stars possess less regular variability and do not demonstrate excellent cycles. This is the first evidence for differences of the solar activity from processes on stars with Excellent cycles. We compare indices of the chromospheric activity of the Sun with that for above 1,300 northern and southern stars whose activity revealed during planet search programs. We argue the matter pro and con for two possible ways of an evolution of activity from a contraction phase to 10 Gyrs. When a young star brakes down, the chromospheric and the coronal activity weaken synchronously. The solar-like activity of the most main sequence F and early G stars does evolve by this path. The activity of the later stars from G5 to K7 after a definite level evolves by another way: the chromospheric activity diminishes up to the solar level, while coronae stay stronger than the solar one. Two possible paths of the evolution of activity are associated with the different depth of the convective zone of these stars. Physically this means that the relative input of small- and large-scale of magnetic fields differs for F–G and K stars.

1 Introduction

Changes of characteristics of activity in timethe evolution of activitybegan to be under investigation during the last 50 years. The HK Project, which was intended to reveal cyclic activity of stars in the solar neighborhood, became a basis for studies

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of the long-term variability of chromospheric activity. X-ray observations of late-type stars also made a major contribution to this field. Already the first results of studies of stellar activity demonstrated that the activity level is related to the axial-rotation rate. This means that angular momentum loss represents a basic factor determining the evolution of the activity. Recently, the rotational periods of stars in star-forming regions in the stage of gravitational contraction were determined directly from observations of the rotational modulation of their optical continuum emission. It was found that the rotational periods of young stars with masses from 0.8 to $1.2 M_{\odot}$ vary from 7 days to about 1 day as the age varies from 1 to 70 Myr [1, Fig. 7]. The subsequent braking of the rotation occurs over significantly larger time scales of billions of years. The rotational period of a star in the deceleration stage is proportional to square root of the age as it follows from Skumanich's law [2], derived from chromospheric observations. This dependence was recently investigated in more detail in the projects "The Sun-in-Time" and "Living with a Red Dwarf" [3, 4]. An analysis of these results for G, K and M dwarf stars confirms Skumanich's law, without the need for any serious changes to it. This became the basis for the development of the method of gyrochronology that follows from combination of two relationships—"activity–rotation" and "rotation–age". This proved to be quite fruitful, since it enables to estimate of the age of the star with a given spectral type (for dwarfs of a given mass) using one parameter only, the level of its chromospheric activity [5]. However, the final correlation for "activity–age" leads to isochrone, which reflects only formally dependence of the level of the chromospheric activity on the spectral class of a star. In many respects this relation is determined by linear relations between indices of the coronal $\log L_X/L_{bol}$ and chromospheric $\log R'_{HK}$ activity. New observational data allow us to construct similar diagram for "chromosphere–corona" indices that can clear up physical aspects of the evolution of solar-like activity.

Current exoplanet-search programs provide as a by-product data on the rotation and activity levels of late-type stars. Indices of chromospheric activity S analogous to the corresponding index in the HK Project have been derived for several thousand F–M stars. The HK Project started in 1966 by O. Wilson at the Mount Wilson observatory was continued afterwards at several observatories, and new S values were reduced to a unified system. This index S is the ratio of the fluxes at the centers of the H and K lines of Ca II at 3,933.66 and 3,968.47 Å to the fluxes at the nearby continuum levels at 4,001–3,901 Å. The line width is 1 Å, and the width of the band at the continuum level is 20 Å. The S index takes into account the contributions of both the chromospheric and photospheric radiations. Later, to exclude the effect of the photospheric radiation, the quantity R'_{HK}—the flux of the stellar radiation in both Ca emission lines normalized to the bolometric luminosity—was introduced in place of S [6] (see [7] for details of the reduction from S to R'_{HK}). This transformation is well calibrated only for color indices $0.44 < B{-}V < 0.9$, whereas it becomes more uncertain for redder stars.

Thus, the chromospheric activity index R'_{HK} can be estimated only for F, G and K stars, and cannot be derived for M stars due to their weak blue (UV) continuum.

There are now more than 1,300 stars with reliable determined R'_{HK} indices. This dataset can be used to study the place occupied by solar activity among processes occurring on other late-type stars at a qualitatively new level, and to trace the evolution of solar-like activity from ages of 500 Myr to 10 Gyr. Considering these data together with current soft X-ray observations, we will analyze the relationship between the activity levels in the chromosphere and corona. In conclusion, we will discuss the consequences of our analysis of this larger amount of material for understanding of solar-like activity on late-type stars of various ages.

2 Chromospheric Activity of Late-Type Stars

Let us consider data on chromospheric activity obtained during exoplanet-search programs. The "California and Carnegie Planet Search Program" at the Keck Observatory has carried out a survey of the Northern Sky over 6 years. The HIRES echelle spectrometer mounted on the 10-m Keck Telescope operated at 3,850–6,200 Å with the high resolution of 67,000. The high signal-to-noise ratio of these data enabled the reliable detection of the H and K line fluxes not only for F, G and K stars, but also for M dwarfs [7]. The "The Magellan Planet Search Program" targeted at southern stars was started with the 6.5-m telescope of Las Campanas Observatory in Chili in the Autumn of 2002. These observations have been done using the MIKE echelle spectrograph yielding spectra at 3,900–6,200 Å with a resolution of 70,000 in the blue and 50,000 in the red. The first results of monitoring of the chromospheric radiation of several hundred late-type stars were recently published [8]. The final observational data for both surveys were reduced to a unified system corresponding to that adopted for the Mt. Wilson HK Project.

We combined both the northern and southern observations, and chose stars with trustworthy R'_{HK} values. All M stars were eliminated automatically by this approach, as well as duplicate targets. The final list of 1,334 stars contains F, G and K dwarfs with color indices $B - V \leq 0.9$.

Figure 1 presents the indices of chromospheric activity R'_{HK} for the entire set of observational data. Figure 1a shows that the vast majority of stars are G stars, with R'_{HK} indices between −4.9 and −5.1. This is also illustrated by the histogram in Fig. 1b. A number of stars are characterized by higher activity levels, compared to most of the objects. Their chromospheric activity is close to the level typical of younger Hyades stars with ages of about 600 Myr. The corresponding isochrone is drawn in Fig. 1a. Similar results were obtained for northern stars in [9] and for southern stars in [8]. Several authors have noted the bimodal character of the activity distribution that can be traced in Fig. 1b. The corresponding centers of the distributions are $\log R'_{HK} = -5.01$ and −4.53, and the distributions have widths of 0.25 and 0.31, respectively.

Such a large observational dataset enables study of the place occupied by the Sun among other late- type stars. For definiteness, we took the chromospheric index

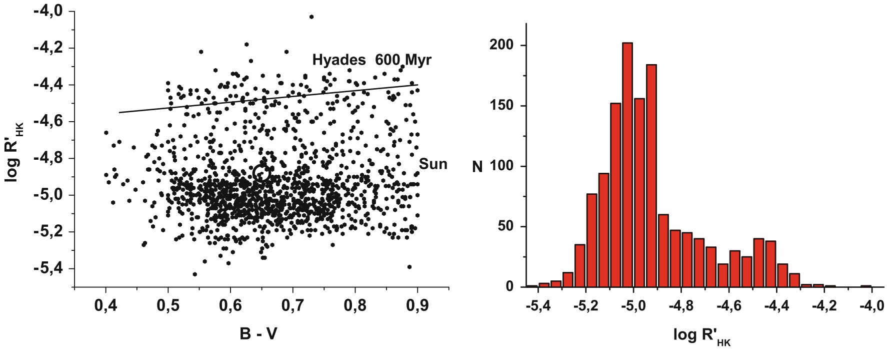

Fig. 1 Chromospheric activity of northern and southern stars recorded during exoplanet-search programs: (**a**)—chromospheric-activity index versus color index. The Sun is marked as a *circle* with $B - V = 0.65$. The isochrone is drawn for the age of the Hyades, 600 Myr; (**b**)—histogram of the number of stars with specified chromospheric-activity indices. The step in log R'_{HK} is 0.05

log R'_{HK} for the Sun to be −4.88, which corresponds to epochs of relatively high activity (Wolf numbers of about of 80). The chromospheric activity of the Sun is clearly higher than for the overwhelming majority of stars in the solar neighborhood. Of course, differences in this parameter of a few hundredths are small, but can be significant when studying the formation of cyclic activity.

Note that our analysis reveals the existence of a certain number of F, and G stars whose activity is much weaker than the activity of the Sun, and even of most stars. This follows from both Fig. 1a, b.

3 Comparison of Chromospheric and Coronal Activity of Late-Type Stars

The appearance of a wider array of observational data for active late-type stars enables us to return to a comparison of the activity developing in different layers of the outer atmosphere. Observations in the soft X-ray can be used to compare data on the activity of late-type stars in the chromosphere and corona. We adopted ROSAT measurements for most of the stars (see, for instance, [10, 11], and used XMM-Newton data for several dozen stars [12, 13]. We adopted the X-ray-to-bolometric luminosity ratio, L_X/L_{bol}, as an index of coronal activity.

We obtained the coronal activity index log L_X/L_{bol} by reviewing the available soft X-ray data: XMM Newton observations, ROSAT data, and a few measurements of X-ray luminosities reported in [14]. Although the X-ray fluxes measured for the same star by two spacecraft were usually very close, in some cases, the difference exceeds an order of magnitude. This is primarily associated with variability of sources observed at different times. These few cases were analyzed in more detail,

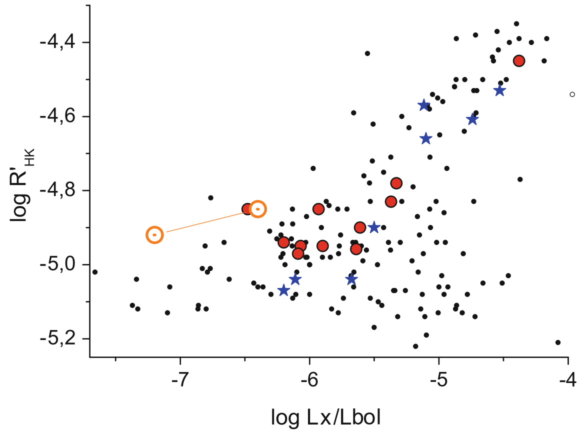

Fig. 2 The diagram of the chromospheric and the coronal activity for the late-type stars. The stars of the basic data set are marked as *dots*. Accordingly to the type of a cycle, the stars of group "Excellent" are marked as *circles*, the stars of "Good" group are indicated as *asterisks*; the Sun at the maximum and at the minimum is denoted its own sign, connected by the *direct line*

and evidence was found for the possible development of flares on the star, or the presence of long-term changes in other energy ranges. As a result, we obtained a dataset for 172 stars (including the Sun) with certain indices of chromospheric and coronal activity (Table in [15]). Figure 2 shows a comparison of the chromospheric and coronal luminosities of the selected stars. Stars with Excellent and Good cycles detected in the HK Project are denoted by various symbols, as in our previous papers [16, 17]. Here, we also show the values for the Sun at its minimum and maximum activity. Adding new objects, most of which have lower levels of chromospheric activity, has significantly changed the general form of the dependence of log R'_{HK} on $\log(L_X/L_{bol})$. Of course, this reflects the basic fact that the activity level of the outer atmosphere is determined by the rate of axial rotation of the star. This is manifest most strongly in the existence of the previously discovered linear relation between the activity indices. However, in addition, some F and G stars with low chromospheric-activity levels (discussed in connection with Fig. 1) are located lower than the stars with cycles along the horizontal axis. These stars possess quite powerful coronas; i.e. their L_X/L_{bol} ratios are one to two orders of magnitude greater than that of the Sun at its maximum activity. Note that stars with detected exoplanets are characterized by fairly powerful coronas and very different levels of chromospheric activity. In [5], the linear relation for the entire interval of activity indices was given by

$$\log R'_{HK} = -4.54 + 0.289[\log(L_X/L_{bol}) + 4.92] \quad (1)$$

This reflects the behavior of points only in the upper branch of Fig. 2, where chromospheric activity increases with rise of the coronal radiation. The addition of active stars detected during exoplanet search programs increased the number of objects with chromospheric activity indices below log $R'_{HK} = -5.0$. In accordance with the above formula, it was expected that the new points would fill the lower left corner of the diagram. However, they are located almost uniformly along the horizontal axis at roughly similar low chromospheric activity levels. In other words, we have discovered a group of stars with chromospheric activities lower than the minimum level for the Sun, whose coronal radiation spans a broad range. Among them are stars with weak chromospheres and strong coronae. The appearance of stars with slowly varying chromospheric activity in the region where the X-ray luminosity changes substantially suggests the presence of a second branch on this diagram. The difference between these branches is such that the upper branch has a comparatively greater number of F stars and the lower branch a greater relative number of K stars. Figure 2 shows the presence of a number of objects with fairly powerful coronae (with about $\log(L_X/L_{bol}) = -5$) situated between these branches.

4 Features of the Cyclic Activity of the Sun

To understand the physical processes leading to the diversity of solar-like activity phenomena in late-type stars of different ages, it is helpful to consider some results of solar researches. We will briefly discuss the following issues: (1) the general character of the solar cycle and the relationship of phenomena to magnetic fields on various scales; (2) characteristics of the differential rotation; (3) the simultaneous manifestation of cycles of different durations.

The variations in the monthly average Wolf numbers for all 23 cycles show epochs of very low activity, an extreme example of which was the Maunder minimum, and of high activity, as in the late 1950s. It has been suggested to call such epochs Grand Minima and Grand Maxima [18]. In spite of the very different lengths of series of observations, some stars with Excellent cycles show more regular cyclic variations of their chromospheric emission.

Activity on the Sun is associated first of all with development of regions of local magnetic fields. But because the Sun is close to us, we are able to study in details some phenomena on the surface which do not effect on the brightness and other characteristics of the Sun as a star. Influence of the large-scale magnetic fields manifests itself in formation of coronal holes as well as in a tendency of appearance and existence of active regions near to definite longitudes at some epochs of the cycle. Besides, the evolution of the large-scale magnetic field determines the drift of active regions from high latitudes to the equator during the cycle (the butterfly diagram). Some non-stationary processes related to the large-scale magnetic field act as triggers for events occurring near spots, which are indicators of strong local fields. This has recently been observed during multiwavelength observations of solar flares.

We share the view that, although activity is associated with local magnetic fields, activity on the Sun is regulated primarily by large-scale magnetic fields.

When we began our studies of the differential rotation of HK Project stars, we expected the differential rotation of stars with Excellent cycles to be similar to that of the Sun. We selected 20 stars, including both such stars and others with less

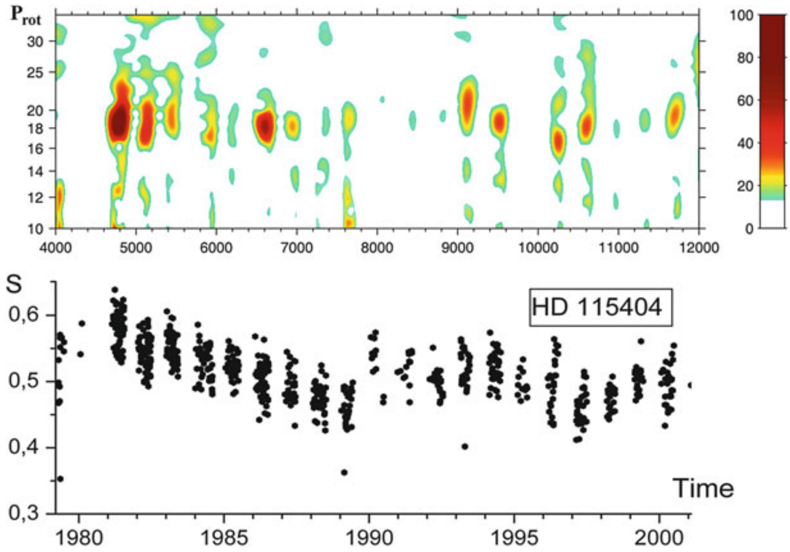

Fig. 3 (**a**) The "period-time" diagram for the star HD 115404. The scale of amplitudes of the wavelet transformation A on the right side is normalized to 100; the rotational period is given in days; (**b**) the temporal behaviour of the S index of the chromospheric activity. From [19]

regular activity (with Good cycles and others). Our wavelet analysis of the long-term variations of the S index of chromospheric activity for all of these stars gave a surprising result: spin-down of the rotation of large-scale inhomogeneities at epochs of high activity, repeating near the maximum of each cycle [19]. This is illustrated by a result for the star HD 115404 with the Good-pronounced 12-year cycle (Fig. 3). The mean period of rotation of surface inhomogeneities of this star of 18.5 days increase in 3–4 days in the epoch of the first observable maximum of the cycle near 1981 and this effect repeats 12 years later at the next maximum. The degree of the differential rotation is estimated as 0.14 that is close to the corresponding solar value. For another star with the Good cycle HD 149661 this value is twice smaller. Under certain assumptions it becomes possible to construct stellar butterfly diagrams.

Further we compare these results for stars with available data concerning solar differential rotation (see e.g., the review in [20] obtained with various techniques of measurements of differential rotation ranging from Doppler shift, Doppler feature tracking, magnetic feature tracking, and p-mode splitting. We confine ourselves to data of the brightness of the solar corona in the Fe XIV 5,303 Å coronal green line. These database collected by J. Sykora (Slovakia) for several solar cycles from 1939 to 2001 presents the daily measurements on the eastern (E) and western (W) limbs carried out for every 5° of latitude and recalculated to the central meridian.

A detailed study of the coronal rotation over the several last cycles is presented in [21] (see also references therein), which considers data on the brightness of the

Fe XIV 5,303 Å coronal green line. The rotation at various solar latitudes was determined from data averaged over six Carrington rotations. Among the main conclusions of [21] is that differential rotation occurs during the entire growth phase of the solar activity, while the rotation is close to rigid-body in the middle of the decay phase.

We proposed new representation for this database for calculation the total emission of the solar corona for each day of observations. We introduced as a new index of the solar activity GLSun (The Green-Line Sun) that is proportional to the total emission of the green corona behind the limb and on the visible disk. This index is purely observational and is free of the model-dependent limitations imposed on other indices of coronal activity. The GLSun index describes well both the cyclic activity and the rotational modulation of the brightness of the corona of the Sun as a star. The GLSun series was subject to a wavelet analysis similar to that applied to long-term variations in the chromospheric emission of late active stars. The brightness irregularities in the solar corona rotate more slowly during epochs of high activity than their average rotational speed over the entire observational interval [22].

Our research shows that solar activity differs from the activity of stars with well-pronounced Excellent cycles, primarily K stars. This could be related to either age differences or differences in the role of the large-scale magnetic fields. Returning to Fig. 2, we note that half the stars with Good cycles are adjacent to stars with well-defined cycles and the Sun, while others are characterized by higher chromospheric and coronal activities.

Solar investigations allow us to study in details the role of magnetic fields of different scales in formation of activity. So, observations of the large-scale solar magnetic field (synoptic maps) and measurements of the magnetic field of the Sun as a star (the total magnetic field) are used to determine the dipole magnetic moment and direction of the dipole field for three successive solar cycles [23]. Both the magnetic moment and its vertical and horizontal components vary regularly during the cycle, but never disappear completely. A wavelet analysis of the total magnetic field shows that the amplitude of the 27-day variations of this field is very closely related to the magnetic moment of the horizontal dipole.

The interval of slower rotation of the irregularities is close to the epoch when the Suns field represents a horizontal magnetic dipole in each activity cycle, but is somewhat longer than the duration of the polarity reversal in both hemispheres [22]. The difference between the periods for the slower and mean rotation exceeds 3 days, as is typical for some stars with higher but more irregular activity than the Sun.

The largest-scale magnetic fields also affect the shape and development of coronal streamers. In the course of the cycle, the neutral line of the longitudinal magnetic field locates near the equator at the minimum and moves away up to 30–40° during other epochs. So, one can distinguish hills of an unipolar field or giant cells of diameters of 0.3–0.5 solar radius. Typically, active regions locate presumably close to the neutral line and the chromosphere above it is the brighter than averaged over the disk. Many coronal loops occur also above the neutral line.

In a certain sense we can speak about effect of magnetic fields of intermediate scales on activity.

As for the solar cycle, changes with a period of 10–11 years are expressed most clearly. However, there are some indications of other changes with shorter and longer periods. Apart from the 22-year magnetic cycle, we can note changes in various indices with a quasi-biennial period, as well as the secular 80–100-year cycles. The simultaneous existence of cycles of different durations on the Sun and some active late-type stars in the Good cycle group suggests that the solar cycle has not entered a strict asymptotic regime (see, for instance, [17] and references therein).

Thus, solar activity is due to a complex interaction of phenomena associated with the evolution of magnetic fields of different scales. Of course, this has only begun to be studied for stars. It may be that it is possible to observe effects associated with large-scale and fields on the Sun because the depth of the convective zone is small, and processes in the tachocline (the transition from the radiative to the convective zone) determine the appearance of the surface magnetic field of large scales. This field governs the development of solar activity. There is evidence that local fields can arise and be amplified directly beneath the photosphere. Thus, there are apparently two levels on the Sun where the dynamo process is realized. This new concept of a two-level dynamo may be useful for our understanding of solar-type activity on other stars.

5 Possible Evolutionary Paths for Solar Activity

Thus far, we have considered stars with activity levels comparable to the solar level. The activity of young stars is substantially higher, and reaches even a saturation level for some stars. In soft X-rays this saturation corresponds to values of $\log(L_X/L_{bol})$ close to −3. There is also the flux saturation in other energy ranges (e.g., the chromospheric emission). It is interesting to consider how the activity of young, low-mass stars evolves after the deceleration of their rotation (after ages of 70–100 Myr).

Let us consider the diagram in Fig. 2, adding the region of stars with saturated chromospheric and coronal activity, shown by the oval in Fig. 4. The linear relationship according to the formula given in Sect. 4 is also shown. This can be regarded as one evolutionary path for the activity as the rotation slows, that is characterized by simultaneous decrease in the chromospheric and coronal emission.

Further we add a set of late-type stars with registered Li I 6707 A line to above considered stars of solar vicinity, including the HK Project stars, as well as to objects, whose activity had been studied in the course of the exoplanet search programs [7]. Based on observations carried out on the Haute Provence observatory [24] we chose G and K stars with measured lithium abundances, for which the index of the chromospheric activity has been determined earlier.

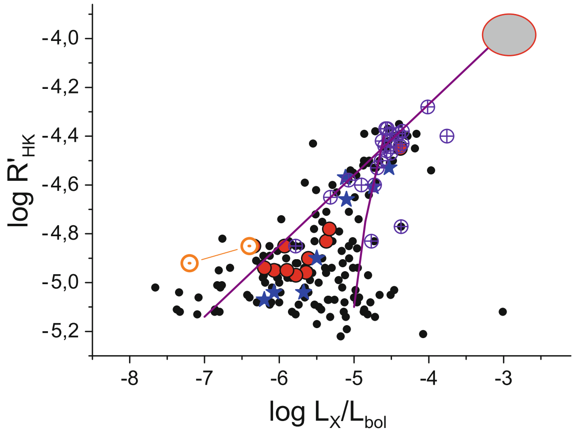

Fig. 4 Schematic illustrating two paths for the development of solar-like activity. Notation is the same as in Fig. 2. The investigated stars with measured lithium abundance and with direct measurements of log R'_{HK} indices are marked as *crosses* inside the *circles*. The area where the chromospheric and coronal fluxes are saturated is shown by the *grey oval*. The *straight line* corresponds to the expression (1)

In Fig. 4 it can be seen that the stars with heavy lithium are characterized by high activity level. Those newly added stars fill up the area, corresponding to the transition from the stars with the solar-like activity to the objects with saturated activity levels. The stars with saturation of the activity level were studied in detail by [25].

In Fig. 4 several stars with detected Li also deviate downwards the linear dependence. Such a trend can mean that there is another way for the evolution of solar-type activity beside a main path which is a basement of one-parameter gyrochronology (the straight line accordingly to the expression (1)). Namely, starting from a definite activity level of many late G and K stars, the chromospheres become weaken while coronae stay still powerful. Both paths shown conditionally in Fig. 4 can be considered as envelopes for all possible ways for the evolution of solar-like activity depending on masses and individual properties of stars. Note that stars with the Excellent cycles also deviate from the main linear relationship.

What is a cause of differences in activity of both groups of stars? The first group of stars adjacent to the straight line in Fig. 4 is characterized by a significant role of large-scale magnetic fields in addition to local magnetic fields in the formation of activity. Evidence for this includes various observational effects, such as the existence of active longitudes, analogs to the Maunder butterfly diagram, and the appearance a short cycle along with the main one. Solar-like activity appears in stars starting from spectral type F5, when the convective zone has a particular small depth of about 0.05 stellar radii. For stars of spectral type G4, the depth the convective zone begins to exceed 0.35 stellar radii. For stars with this range of parameters, the dynamo process probably develops in both the tachocline and sub-photospheric layers.

It is often supposed that large-scale magnetic fields occur near the lower bottom of the convective zone, whereas local fields are formed at relatively shallow depths beneath the photosphere. When the convective zone becomes sufficiently thick (over 0.35 stellar radii), processes close to the bottom of this zone cease to affect the formation of solar-type activity at the surface.

For later-type stars, up to fully convective red dwarfs, the evolution of their activity is determined by processes occurring directly beneath the photosphere, where the dynamo mechanism generates local magnetic fields. For stars with spectral types later than G7 (color indices $B - V > 0.67$) and the thicker convective zone, effects of magnetic fields generated near its bottom are inconsiderable.

6 Discussion

The most extensive information on cyclic activity available for the closest to us star—the Sun. Our investigation of active late-type stars allows us to separate a new group of stars on the "chromosphere–corona" diagram that is an evidence for existence of two possible paths of the evolution of solar-like activity. How does this help to understand features of the cyclic activity of the Sun and to imagine what was activity of the young Sun and what happens with the Sun in the future?

The appearance of spots, plages etc. on the solar surface is associated with local magnetic fields, but activity of the Sun as a whole govern by the large-scale magnetic field. This is inherent in the main group of stars where large-scale magnetic fields are observed directly, active longitudes exist, and activity expands to all atmospheric heights. The activity level of these stars is higher but is less regular than that of the Sun. Of course, the Sun is quite old star; its chromospheric activity is higher than that of stars of the similar age, while the solar corona is substantially weaker.

The conception about possible paths for the evolution of solar-type activity fits into those ideas that can explain features of effect of large-scale magnetic fields on activity and its relation with the depth of the convective zone. The large-scale magnetic field generated near the lower boundary of the convective zone governs activity both on the Sun and the most of stars of the main group. If these ideas for the Sun are formulated during last years thanks to success of the local helioseismology, so for stars we point out the first reasons for application of two-level dynamo.

What conclusions can we do from the proposed suggestion for the explanation of the physics of the cyclic activity of the Sun on various stages of its evolution? The basic features of activity of the Sun and the main group of stars, whose chromospheric and coronal radiation change simultaneously at large time scales, are similar in many respects. This relates to observable signs of large-scale magnetic fields, i.e. active longitudes, some instability of the cycle like different amplitudes and simultaneous presence of several periods of long-term variability. Despite the old age, the Sun does not yet reach that level of chromospheric activity that is characteristic for the most of late-type stars (Fig. 1). This can be associated with peculiar properties of the angular momentum loss after the age of 1–2 Gyr (in Fig. 4 this relates to the region of separation on two branches). A substantial argument for affiliation of the Sun to this group is general properties of their differential rotation [19, 22].

Fundamental difference between the Sun and the stars, whose activity evolves by another path, is distinction in filling factors, i.e. relative areas covered by active regions which are observed the best in the soft X-rays as well as in the area of spots. If the soft X-ray emission of the Sun out of flares variations changes at different time scales, so the later the star is then the corresponding variations are weaker. This reflects growth of number of weak non-stationary events. In Fig. 4 it is seen that coronae of stars located between two lines on the diagram, in particular, of stars with the Excellent cycles are significantly more powerful than the solar corona.

The regular cycle is not typical for the stars of the main group including the Sun, but this is characteristic for old low-rotating K stars. This can mean that access on the asymptotic regime of the dynamo with regular cycles occurs easier in the case when activity is governed by local magnetic fields.

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