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Solar-Type Activity: Epochs of Cycle Formation

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Abstract—The diagram of indices of coronal and chromospheric activity reveals stars where solar-type appears and regular cycles are forming. Using new consideration of a relation between coronal activity and the rotation rate, together with new data on the ages of open clusters, we estimate the age of the young Sun corresponding to the epoch of formation of its cycle. The properties of the activity of this young Sun, with an age slightly older than one billion years, are briefly discussed. An analysis of available data on the long-term regular variability of late-type stars leads to the conclusion that durations of cycles associated with solar-type activity increase with the deceleration of the stellar rotation; i.e., with age. New data on the magnetic fields of comparatively young G stars and changes in the roles of large-scale and local magnetic fields in the formation of the activity of the young Sun are discussed. Such studies can help identify observational tests aimed at identifying the conditions for the formation of cyclic activity on stars in the lower part of the main sequence, and test some predictions of dynamo theory.

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1. INTRODUCTION

There is now a large number of observations of individual solar phenomena demonstrating various specific features of the present solar activity. Two basic methods can be used to understand the solar activity in the past, during the epoch of formation of the solar cycle. The first deals with the evolution of the angular momentum of the stellar axial rotation and dynamo theory. This provides the possibility of identifying the main factor of the activity's evolution, related to the deceleration of the rotation. The influence of turbulent convection on the general features of the activity is a more complex question. The second method compares observational data on the activity of the Sun and other similar stars. This method has led to the development of the idea of a single parameter gyrochronology relating the activity level to the stellar age [1].

X-ray and optical observations of numerous late-type active stars (detected during searches for planets with large ground-base telescopes and the Kepler Space Mission) allowed us to move forward in comparison with the activity of stars of various ages and the Sun. We mention here new studies of the relationship between the X ray emission and rotation [2] and further development of the gyrochronology based on the comparison between the chromospheric and coronal activity and clarification of the role of magnetic fields on various scales in the formation of the activity [3–5].

We are trying to understand what we can say about the type and level of the Sun's activity at the epoch when the solar-type activity was only beginning to form. It is clear that the activity of some stars is saturated. In other words, the X-rays from the coronas of these stars, or more precisely, the luminosity ratio L_X/L_{bol}, reaches 10^{-3} and depends only weakly on the axial rotation rate. This is the case for stars with rotation periods from 0.3 to 7 days. The ages of these stars are definitely less than 800 Myrs. Their coronas are almost completely occupied by hot regions (with temperatures of about 10 MK), and the spottedness of their surfaces can reach tens of percent. The activity of such stars differs considerably from that of the Sun.

Here, we consider stars that rotate more slowly, whose coronal activity is below the saturation level. At the same time, these stars demonstrate fairly high chromospheric and coronal activity, with no signs of circumstellar disks or dominance of a dipole magnetic field.

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Signs of stellar magnetic activity on the lower part of the main sequence include the formation and development of complexes of phenomena in various atmospheric layers—photospheric imhomogeneities, flares, and coronal holes. The Sun is the best-studied magnetically active star, and its spots have been observed over more than 400 yrs, starting from 1610, the epoch of Galileo. We will call the 11-year cycle (its length was about 10 yrs in the 20th century) the main cycle of solar activity. Its duration has varied from 7 to 17 yrs at various epochs, and the amplitude of the maxima vary over a cycle of 70–100 yrs (the Gleissberg cycle). The most reliable data to improve the accuracy of estimates of sunspot activity and analyses of the 11-year cycle are the Wolf numbers $W(t)$, which have been recorded since 1849. Relations between the areas and the total magnetic fluxes of sunspots have been reliably determined, as well as regularities in the appearance of global maxima and minima in the solar activity [6].

The solar activity is undoubtedly connected with the evolution of magnetic fields. In the past, this was taken to be associated with sunspots, which were viewed as hills of magnetic fields. Sunspots are included in active regions occupying comparatively small areas of the surface. In addition to the local magnetic fields of active regions, there also exist weaker large-scale fields. The dipole magnetic field of the entire Sun is observed near the solar poles, and this field changes sign every 11 yrs. This polarity reversal of the global dipole field occurs near the cycle maximum. Thus, the configuration of the large-scale magnetic fields is re-established every 22 yrs, forming a magnetic cycle.

Studies of the cycles of stars in the lower part of the main sequence were begun relatively recently, in the middle of the 20th century. The basis of these studies is the works of Wilson [7, 8], which were devoted to the analysis of the intensities of the CaII H and K lines as an indicator of chromospheric activity; these studies were successfully continued in the HK project. This analysis of data series obtained over intervals of more than 30 yrs has shown that 85% of 111 objects studied are variable, with cyclic variations with durations of about 7 yrs found in 60%, linear trends on scales of $\sim$25 yrs or more found in 12%, and irregular variations found in 13% [9]. Relationships between the cycle characteristics (amplitudes and periods) and the stellar parameters have been found, and the activity level has been studied for various groups of stars with various ages and convective-zone depths.

Projects continuing studies of stellar chromospheric activity are being carried out at many observatories. Programs of systematic studies of photospheric activity were started in the 1990s [10]. Data from the All Sky Automated Survey (ASAS) and the MOST, CoRoT, and Kepler space projects are being used for a number of studies. Spot cycles similar to the 11-year solar cycle have been found, as well as cycles involving changes in the active longitudes and the areas and distributions of spots; these must be taken into account in an analysis of stellar cycles. Examination of the evolution of stellar activity for various groups of F–M stars has shown that dynamo processes occurring at different levels of the convective zones are responsible for the cycle formation.

Various solar phenomena are associated with both large-scale fields (coronal holes and active longitudes) and local fields (active regions and spots). Both the large-scale fields and the quasi-biennial cycle are probably related to dynamo processes occurring near the base of the convective zone, at the tachocline at a depth of 0.3 solar radii. On the other hand, according to helioseismology data, the bases of sunspots are located only 40–50 thousands km below the photosphere. This means that local fields are directly related to phenomena occurring beneath the photosphere.

The evolution of activity on time scales of about a billion years was studied in [3], and evidence was found that cycles are formed at a definite stage of an evolution of activity. Since the type and level of activity depends on the axial rotation rate of the star, it is necessary to ascertain the relationship between characteristics of the cycle and the periods of axial rotation. The studies [11–13] were devoted to this problem (see also the review [14]). These studies repeated earlier analysis, supplementing the HK-project data with more recent observations. However, the authors note that the samples studied contain objects of various types, including binary stars. Due to the insufficiently frequent observations and their total duration of the observations, it has not been possible to reliably estimated the cycle durations, especially when only a few periodic variations have been observed for a single star.

The goal of our present study is to clarify the conditions under which regular cyclic changes in activity are formed. We focus mainly on estimates of the stage of the evolution of the activity when the cycle is formed. First and foremost, we have re-analyzed the relationship between the cycle duration and the rate of axial rotation using only reliable data. We have also tried to identify the physical conditions under which the chaotic behavior of plasma motions is transformed into regular cyclic changes. Such studies can facilitate the development of dynamo theory and our understanding of magnetic activity.

2. WHEN IS THE CYCLE FORMED?

In addition to data on the long-term variability of the chromospheric radiation of more than 100 of the nearest stars studied in the HK project, information on chromospheric activity has been obtained in searches for exoplanets in the Northern and Southern hemispheres. An analysis of these observations can be found in [3], where it is shown that the index of chromospheric activity $\log R'_{\rm HK}$ for G stars varies within narrow limits from −4.9 to −5.1. Note that the level of the solar chromospheric activity near the cycle maximum, $\log R'_{\rm HK} = -4.85$, exceeds the level of the main group of these stars. Younger stars of the Hyades Cluster were also studied in [3]. Various activity levels are shown in the histogram in Fig. 1a, where the second maximum with higher activity includes stars with ages of about 600 Myrs in the Hyades.

In addition to field stars and open clusters, stars with high spatial velocities were observed in the far ultraviolet (FUV: 1350–1780 Å) by the GALEX (GALaxy Evolution EXplorer) spacecraft [15]. UV photometry has revealed stars with both high and low activity levels among the 1360 stars studied. Figure 1b presents a histogram of the level of chromospheric activity for these stars. Comparing the two histograms in Fig. 1, we can follow the evolution of the chromospheric activity as a function of age (the three maxima in Fig. 1b for $\log R'_{\rm HK} = -4.45$, −4.8, and −5.0).

Modern data enable comparisons of the levels of chromospheric and coronal activity of low-mass stars of various ages. Figure 2 presents a diagram showing the main branch of stars connecting stars with low activity levels and saturated stars. The straight line connects young stars with ages of hundreds of millions of years and old stars with ages comparable to or exceeding the solar age (4.5 Gyrs). This dependence differs only slightly from the one found earlier in studies of single-parametric gyrochronology [1]. This means that the axial rotation is indeed the main factor determining activity levels.

We analyzed the chromosphere–corona diagram earlier; we focus here on stars with clearly pronounced cycles. According to the classification of the HK project, stars with Excellent and Good cycles are concentrated along a straight line in the chromosphere–corona diagram that is close to the line for the single-parametric gyrochronology. All these stars are bounded from above by a certain level of chromospheric activity. The star with Excellent cycle, V2292 Oph (HD 152391, G7V) is also located in the same place, with $\log R'_{\rm HK} = -4.4$; this activity significantly exceeds the levels of the remaining stars with pronounced cycles.

Most BY Dra-type stars are located in a compact region in the chromosphere–corona diagram, in the region $R_X = \log(L_X/L_{bol}) = -4.5$ and $\log R'_{\rm HK} = -4.4$. The activity of late-type stars is characterized by variability of the optical continuum associated with their axial rotation. This is usually indicated by the presence of surface inhomogeneities (mainly cool spots). Stars with numerous spots are classified as BY Dra variables. In addition to the rotational modulation, some of these stars display long-term variations in their optical continuum, which are sometimes regular or cyclic. Stars of this type possess fairly high activity at all altitudes in their atmospheres. For example, the area occupied by spots can exceed the spotted area at the solar maximum by a factor of 100.

In general, BY Dra variables form a large class of objects, including both comparatively young stars with noticeble lithium abundances and older stars with low chromospheric activity (Fig. 2 presents only some of these stars, studied in connection with detection of their lithium abundances). Note the significant number of binary stars among objects of this type. This binarity may be related to the fact that these stars maintain high activity over longer time scales than do similar single stars. This has been attributed to interactions between the angular momenta of the orbital and axial rotation. Thus, the diagram allows us to indicate the region to which stars with cycles extend. We wish to clarify the epoch in a star's life when a regular cycle arises. It is well known that the scale of stellar ages in the lower part of the main sequence is based on observations of open clusters. The rotation of most stars in such clusters decelerate with time, due to the loss of the angular momentum of the stellar rotation via the outflow of the magnetized stellar wind. The ages of these clusters can be taken to be known from stellar-evolution computations. Young open clusters are fairly well studied up to the Hyades Cluster, whose age is about 600 Myrs—closest to the region of interest, $R_X = \log(L_X/L_{bol}) = -4.5$ and $\log R'_{\rm HK} = -4.4$ in the chromosphere–corona diagram. We can consider the scale of ages of low-mass stars to be well determined, from hundreds of millions to billions of years [16].

Considerable progress in the development of gyrochronology was achieved in [17], where an index of coronal activity is expressed through a combination of parameters such as the radius and rotation period (L_X/L_{bol} is proportional to $R^\alpha P^\beta$). This makes it possible to reduce the spread in the observed ratio L_X/L_{bol} as a function of the rotation period. Note that this analysis does not use the Rossby number, although L_X/L_{bol} clearly depends on this quantity. We used the physically reasonable solution [17] with

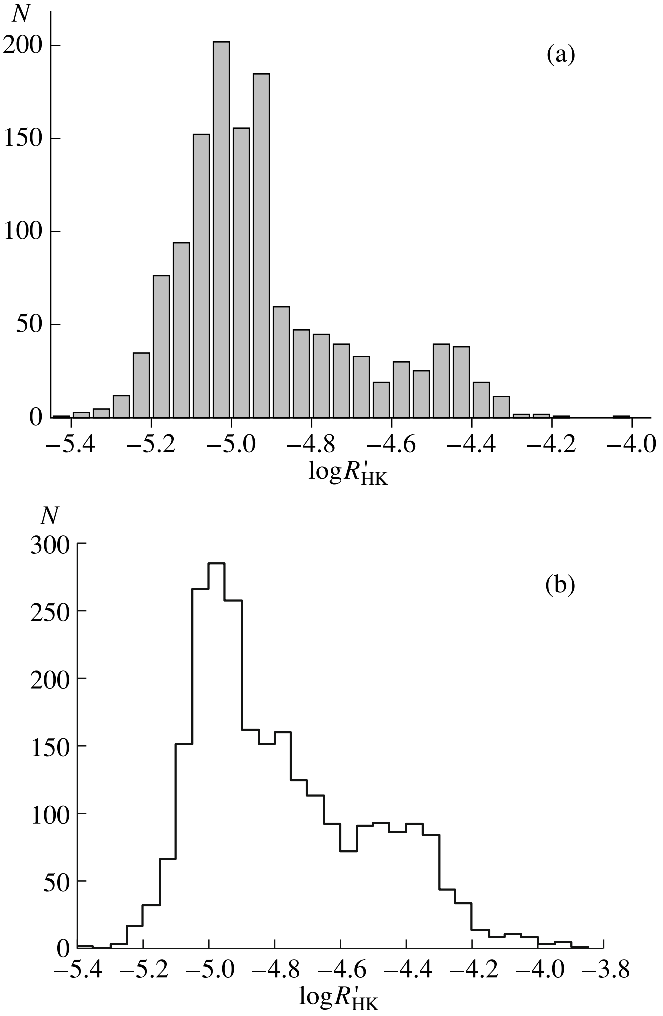

Fig. 1. Distribution of levels of chromospheric activity according to (a) data from searches for exoplanets and (b) GALEX space observations [15].

the parameters $\alpha = -4$ and $\beta = -2$, which corresponds to the proportionality coefficient $k = 1.86 \times 10^{-3}$. The X-ray luminosity for unsaturated regions is $L_X \sim P_{rot}^{-2}$, in agreement with the conclusions of [18, 19]. However, there are no active stars with the solar luminosity with rotational periods P_{sat} shorter than 1.6 days (see formula (10) in [17]). It is known that this regime with saturated activity corresponds to $L_X/L_{bol} \sim 10^{-3}$, and depends very weakly on the rotation period.

There exist some stars with periods from $P_{sat} =$ 1.6 days to $P_{sat} = 10$ days whose activity is either saturated or below the saturation level. Let us note two characteristic features of stars with similar periods. First, these stars have lithium abundances only slightly lower than those of young stars that rotate with periods of several hours. Second, the activity of such stars clearly depends on the stellar radius: changes of 5–10% in the observed radii affect both the activity and the lithium abundance.

Thus, a refinement of the age scale together with a new analysis of the relationship between activity levels and rotation periods makes it possible to determine stellar ages in the interval from 100 Myrs to several billion years. For example, the selected region in the chromosphere–corona diagram where $\log(L_X/L_{bol}) = -4.5$ corresponds to the rotation periods of 10.5 days. This value is supported by a preliminary analysis of cluster data obtained by the Kepler spacecraft [16]; in particular, there is a single relation between the rotation periods and the masses of late-type stars in NGC 6811, with an age of one billion years. It is shown that, for solar-mass stars, a rotation period of 10.8 days corresponds to this age.

We can conclude that solar-type activity is established in G stars with rotation periods ≥10 days, and,

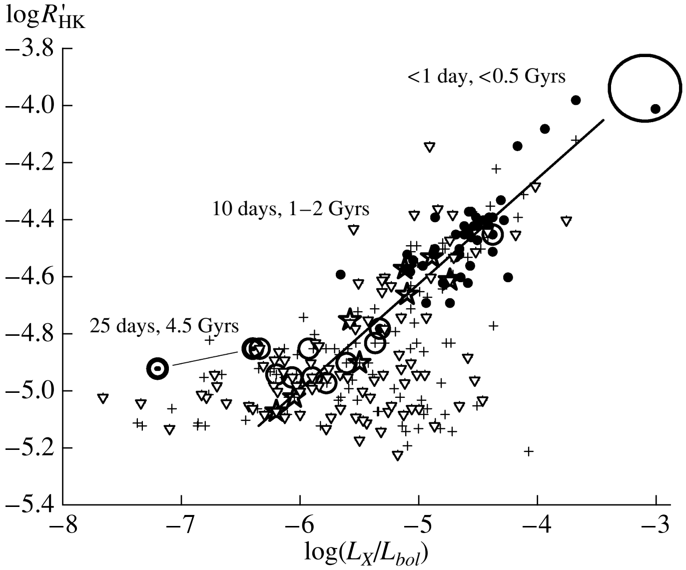

Fig. 2. Indices of chromospheric and coronal activity for active late-type stars. Saturated stars are indicated by an ellipse. The straight line corresponds to the main scenario for the evolution of activity [3], and almost coincides with the line corresponding to the single-parametric gyrochronology [1]. The stars below the line apparently correspond to another activity-evolution scenario [3]. Stars with Excellent cycles are shown by empty circles, stars with Good cycles by asterisks, BY Dra-type stars by filled circles, stars with high proper motion by triangles, and field stars by crosses. The points for the Sun at its cycle maximum and minimum are connected with a line segment. The periods of axial rotation and stellar ages for given levels of chromospheric activity are also indicated.

consequently, with ages ≥1 Gyrs. These phenomena are well studied for the present-day Sun. Physical processes resulting in the formation of spots, faculae, and flares are determined by specific interactions between large-scale and small-scale magnetic fields. The formation of regular cyclic changes is essential for the solar activity. Further, we will apply the concept of "solar-type activity" to stars with periods of 10 days and longer. We will call a G dwarf with a rotation period of about 10 days, corresponding to an age of one billion years, a young Sun. It is believed that the cycle on such a star has already formed.

Solar-type activity differs from processes occurring on other stars rotating with periods from several hours to several days and demonstrating saturated activity. Though these young stars sometimes exhibit phenomena similar to those observed on the Sun, the role of the large-scale dipole fields dominates on these stars; global restructuring of the entire corona can occur, and the character of nonstationary processes differs strongly from those on the contemporary Sun. For example, the energy and frequency of superflares of G stars differ for stars with periods shorter than and longer than 10 days [20].

Let us briefly describe the activity of the young Sun. A significant amount of hot plasma with temperatures of 5–8 MK exists in coronae of stars of such an age. On the Sun, the maximum of differential emission measure DEM(T) is about 1–2 MK; on the young Sun, this maximum is shifted to 6 MK, and exceeds the present solar value near the cycle maximum by two orders of magnitude. Some parameters of G dwarfs of various ages are presented in the table.

In the portion of the diagram (see Fig. 2) where the BY Dra-type stars are concentrated, V2292 Oph (HD 152391, G7V), with a period of 11 days, is the only star with an Excellent cycle with high chromospheric and coronal activity. Since there are quite a few spots on this star, as on BE Cet, the spots determine the variability of the optical continuum during the cycle, and there is an anti-correlation between the long-term variations observed in the continuum and in the chromospheric CaII H and K lines. It is known that the Sun and other slowly rotating stars possess a correlation between the total radiation of the photosphere and chromosphere. According to estimates presented in [21], the young Sun can display numerous flares with total energies reaching 10^{34} erg, with the occurrence of superflares being one per 500 yrs. The mass loss is estimated to be 10^{-11} $M_\odot$/year, with the relative contribution of coronal mass ejections to the stellar wind being significantly higher than for the present-day Sun. Some parameters of the magnetic fields of the young Sun are also discussed in [21].

Finally, we note that cyclic activity is formed on G and K stars with ages of about 1–2 Gyrs. Starting from this age, we can speak about solar-type activity for low-mass stars.

Parameters of G dwarfs of various ages

Stars	Sp	P_{rot}, days	S, %	L_X, erg/s	R_X	$\log R'_{\rm HK}$
Active Sun	G2V	25	0.3	10^{27}	−7	−4.90
Young Sun		10	3	10^{29}	−4.4	−4.45
BE Cet	G2V	8	3	10^{29}	−4.4	−4.43
κ^1 Cet	G5 V	9		10^{29}	−4.4	−4.42
EK Dra	G0V	3	10–20	10^{30}	−3	−4.15

3. RELATION BETWEEN CYCLE DURATION AND ROTATION PERIOD

Cycles are distinctive features of solar-type activity. If a cycle has already formed at an age of 1–2 Gyrs, the cycle parameters can change in the course of the star's evolution. This question has already been studied using all observed indications of cyclic changes. However, the use of dissimilar data has hindered the ability to draw reasonable conclusions. Therefore, we analyze here only data from the HK project for stars with Excellent and Good cycles [9], that is, with reliable rotation periods and cycle durations. We also added three stars whose cycles were identified through specially held wavelet analyses [22]. We also refined the cycle duration of about 14 yrs for HD 149661 using all observations available from 1965 to 2002. Figure 3 presents the results of our analysis, and shows a tendency for cycles to become longer with decelerating rotation for stars rotating more slowly than the Sun. This suggests that the cycle duration increases with age. Note that this refers to long cycles; we do not consider short cycles here due to the lack of sufficiently reliable data.

It is of interest to investigate this tendency for a more representative sample of stars. The problem is that sufficiently uniform and long-term series of observations are required to establish the cycle durations. At present, these observations have significant errors. Direct comparisons of measured cycle durations and rotation periods for all late-type stars do not display any obvious trends. Three considerations are useful for analyzing this question. First, we should consider long and short cycles separately. If two cycles are identified for a star, the choice is obvious. In the remaining cases, we must apply an additional analysis to determine the group of cycles to which the cycle duration corresponds. Second, we should use the data representation proposed in [11, 13] and examine the relationship between $\log(P_{cyc}/P_{rot})$ and $\log(1/P_{rot})$; i.e., between the number of stellar rotations over the cycle and the rotation velocity. Third, we should not analyze all late-type stars together, since the cycles of M stars result from a number of different and complex processes, hindering identication of a general law for F–K stars with surface convective zones.

We used the information verified to analyze cases where the cycle durations are reliably established for G and K stars (including BY Dra-type stars). We selected 60 stars from the observations of [9, 13, 23] for which only the main cycle, or two cycles, have been determined. In some cases, the reliability identification of a cycle has been based on a wavelet analysis similar to that applied in [22].

Figure 4 presents the results of our analysis. Data on short cycles are based on the photometric observations [13]. The correlation coefficients for the long and short cycles are 0.833 and 0.928, respectively. Linear fits $Y = A + BX$ for the two types of cycles yield the coefficients $A = 3.459$ and $B = 0.918$ for the long cycles and $A = 3.094$ and $B = 0.884$ for the short cycles.

Here, we have used purposely the same data representation as that used in [13]. Although the stellar samples and the methods used to identify the cycles are somewhat different, our results are close to those obtained in [14]. In both cases, the two fitted lines are almost parallel, but our lines are farther from each other than those in [14] (see Fig. 10 in [14]).

Using explicit instead of statistical relationships between the cycle durations and the rotation periods, we find that the relation displayed is fairly weak. Nevertheless, these two independent analyses indicate a common character for the relation discussed. Let us consider the explicit expression for one type of cycle, for example, for the linear fit $\log P_{cyc} = A + (1 - B) \log P_{rot}$. It is clear that $B = 1$ separates two kinds of solutions, in which the cycle duration either increases or decreases with the deceleration of the rotation. The currently available data indicate that it is most likely that the cycle durations increase with increasing rotation period. This conclusion agrees with the results obtained for HK project stars with pronounced cycles presented in Fig. 3.

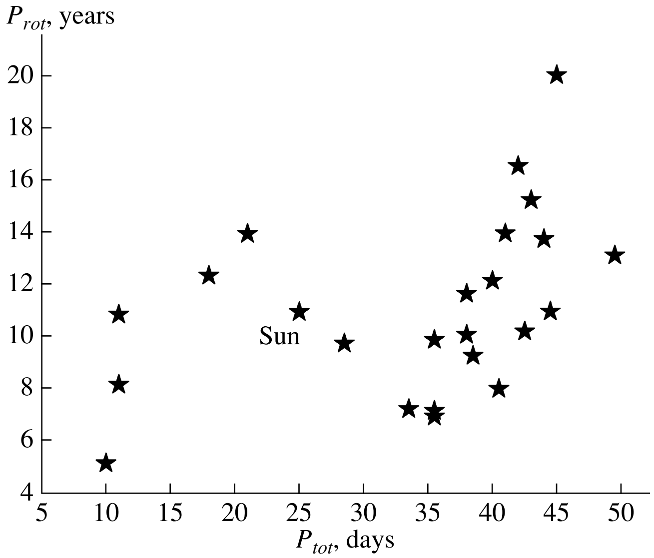

Fig. 3. Cycle duration as a function of the rotation period for stars of the HK project.

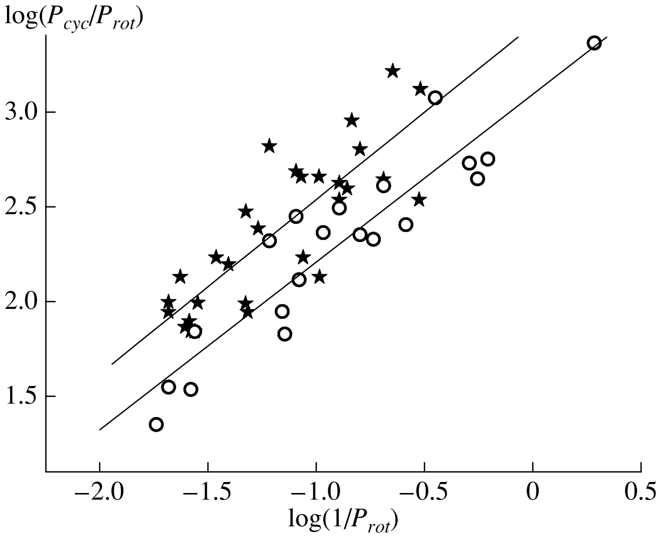

Fig. 4. Comparison of cycle durations and rotation periods for long (asterisks) and short (circles) cycles.

Our analysis enables us to estimate the duration of the solar cycle for the epoch when this cycle was formed and become fairly regular. Since the fitted lines shown in Fig. 4 are almost parallel and most of the durations P_{cyc} ($N = 49$) approach the upper line, we combined the data to obtain a common linear fit for all the P_{cyc} values, with the parameters $A = 3.342$ and $B = 0.840$. This corresponds to cycle durations of 10.2 yrs for the present Sun and 8.7 yrs for the young Sun.

4. DISCUSSION: MAGNETIC FIELDS ON G STARS

Thus far, only a few measurements of the magnetic fields of low-mass dwarfs were carried out. Similar to solar observations, the strength of the field along a line of sight was directly determined from spectra containing one or more magneto-sensitive lines, first and foremost in the visible, and then in the infrared. Such a study of the Zeeman effect for late-type stars revealed spots with field strengths of 1–3 kG occupying up to 10% of the stellar surface. The signal intensities change with the phase of the rotation period. This question has been well studied for only a few stars. Relevant data can be found, for example,

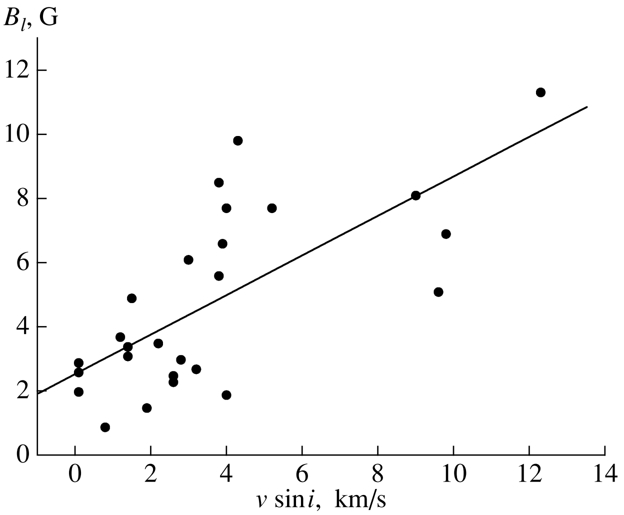

Fig. 5. Magnetic fields of main-sequence G stars. The straight line shows the linear fit to the data.

in [24, 25]. These data mainly refer to K stars (ϵ Eri, 61 Cyg A, σ Dra) and the star ξ Boo A (G8 V). The observed magnetic fields of more active stars with periods of 6 and 12 days agree with a model in which spots with field strengths of about 1.5 kG occupy nearly 20% and 10% of the surface, respectively. The magnetic fields in spots on stars with rotation periods of about 30 days reach 1–2 kG, with the spotted area being about 2%.

These data agree well with current understanding of stellar magnetic fields. First, variations in the magnetic-field strength with the phase of the rotation period, together with spectral data, can be used to model the distribution of inhomogeneities over the stellar surface. This method of Zeeman–Doppler mapping enables the separation of the contributions of spots and large-scale fields, in the first approximation. At the same time, the main regularities, such as the relationships between the mean surface field and the rotation velocity or the total level of stellar activity, are preserved [26].

Thus, we conclude that the general behavior of the magnetic fields of G and K stars is similar to that observed for the present-day Sun: namely, large-scale fields are most distinctly observed in the polar zones and local fields at lower latitudes. The contribution of magnetic fields of various scales to the mean field varies over several years, and depends on the orientations of the rotation axis and the dipole axis relative to the line of sight.

Second, new information on the magnetic fields of solar-type stars has recently been obtained in the BCool Collaboration program [27], in which large telescopes carry out spectropolarimetric observations of 170 late-type stars. From 5000 to 11 000 spectral lines are simultaneously used to measure the magnetic field, making it possible to measure the line-of-sight components of stellar magnetic fields fairly accurately. The quantity B_l is the signal averaged over all observations of a star. These spectral observations can be used to determine both fundamental parameters of the stars and the levels of chromospheric activity. Magnetic fields have been detected in 40% of these stars. The mean line-of-sight field for the K stars is $|B_l| = 5.7$ G [27], which is higher than the fields of both G and F stars (3.3 G).

We have briefly analyzed only the data for G dwarfs, in order to estimate the magnetic-field strength on the young Sun. The technique used has enabled us to detect magnetic fields corresponding to epochs when the global solar dipole reaches its maxima of about 1 G (for example, this was the case of the Sun in 1991 [28]). We took all G stars with B_l exceeding 3σ from Table 3 of [27]. We omitted some rapidly rotating, and thereby some young stars with stronger magnetic fields. The final list includes 28 G stars with periods exceeding 7 days (from approximate estimates based on data about chromospheric indices taken from Table 5 of [27]). Figure 5 presents our results. The field magnitudes $|B_l|$ of two stars, ξ Boo A and 61 UMa, considerably exceed the fields typical for stars with such rotation rates. This probably results from uncertainties in the inclination between the stellar rotation axis and the line of sight [27]. With these two stars omitted, the correlation coefficient between $|B_l|$ and $v \sin i$ exceeds 0.70.

Thus, if we omit stars whose fields are not detected reliably and some stars with very strong fields, we find the mean field $|B_l|$ reaches 4.72 ± 0.53 G for G stars. The relationship shown in Fig. 5 describes the weakening the mean field as the stellar rotation decelerates, i.e., as the star ages. The mean field we have found corresponds to a rotation speed of 4 km/s, which is twice the value for the present-day Sun. We can thus adopt this field strength as the mean field of G stars with rotation periods of about 10 days, corresponding to ages of 1–2 Gyrs.

Let us compare this value with data on the magnetic field of the Sun as a star. The fields averaged over a Carrington rotation do not exceed 0.5 G at solar maxima. Thus, the mean magnetic fields of young G stars exceed the fields of present solar maxima by at least an order of magnitude. Note that our estimate is confirmed by $|B_l|$ estimates for stars whose parameters are closest to those of the young Sun: 8.5 G for V 2292 Oph and 7.7 G for κ^1 Cet (according to different data, the field of this star is $|B_l| = 7.0$ G [29]). This agrees with our general conclusion above.

Information on the large-scale magnetic fields of late-type stars is now becoming available. In particular, slowly rotating stars possess fields with structures similar to those of solar fields, which change regularly in the course of the 22-year magnetic cycle. In other words, a global dipole is almost always present; only during polarity reversals does the magnetic equator move in longitude in a way that can be treated like the manifestation of a large-scale toroidal component. Active regions are located fairly chaotically, active longitudes are poorly observed, and toroidal fields are characterized by comparatively small scales (they are local fields). At the same time, G stars with rotation periods below 12 days display clear large-scale toroidal field components [26]. Though these toroidal fields dominate over the large-scale poloidal fields, the difference in their strengths is rather small. It is difficult to relate these new findings with spot data for rapidly rotating G stars.

5. CONCLUSION

We considered the evolution of solar-type activity in earlier studies. It was noted that stars with cycles are located nearly along a straight line in the chromosphere–corona diagram. Their location almost along the line yielded by single-parametric gyrochronology is simply related to the difference in the ages of stars with Excellent and Good cycles. However, these stars do not occupy the entire line up to stars with saturated activity, and reach only a certain point, with V2292 Oph (HD 152391, G7V), with an Excellent cycle and a rotation period of 11 days located slightly below ths point (BY Dra-type stars are also concentrated there). There are reasons to suppose that this activity level corresponds to the start of solar-type activity with cycles. Using the new relation between coronal activity and rotation rate [17] and new data on the ages of open clusters, we have estimated the age of the young Sun at the epoch of cycle formation. We have briefly discussed the activity of this young Sun, whose age is slightly older than 1 Gyrs. We have used reliable data to compare the cycle durations with the rotation periods, and conclude that the cycles lengthen as the stellar rotation slows. The relationships revealed lead to estimated cycle durations of 10.2 yrs for the present Sun and 8.7 yrs for the young Sun, assuming that the type of activity has not appreciably changed since the epoch when the cycle was established.

It is clear that the solar activity is due to interactions between magnetic fields of different scales. What was the solar activity at the epoch when the quasistationary development of these processes had just begun? Data on magnetic fields and the activity occurring in various atmospheric layers of main-sequence G stars provide answers to this question. The discussion of new data on the magnetic fields of comparatively young G stars presented here can be helpful for identifying the conditions required for the cycle formation. Note also that observational facts can also be used to refine the dynamo theory.

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