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Activity of the Sun in the Age of 1–2 Gyr[1]

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Abstract—We discuss basic properties of the solar activity in the modern epoch and the further development of ideas about estimate the age of stars by the level of activity (gyrochronology). From comparison of properties of solar activity and processes on other G stars we have determined activity levels of the chromosphere and corona of the young Sun in its age of 1–2 Gyr. So, activity of the Sun in such an age is closest to the processes in the G stars, HD 152391 (V2292 Oph) and HD 1835 (BE Cet) with the rotational periods of 11 and 8 days correspondingly. The total spot area is of 2–3 orders of magnitude higher than the current value at the maximum of the solar cycle, the activity levels of the chromosphere and the corona are quite high and similar to the Hyades, but it did not reach the saturation level. We have analyzed new measurements of longitudinal magnetic fields and distribution of the toroidal and poloidal fields on the G main sequence stars. The mean value of the longitudinal fields for active G stars is of one order of magnitudes stronger than the mean daily magnetic field of the Sun as a star, for instance those during the 21th cycle maximum. Besides, the detection of large-scale toroidal magnetic field in such stars is important. Taking into account the activity levels and magnetic fields, we analyzed data on superflares on G stars registered with the Kepler mission. We have defined the upper limit of energy of flares that can occur in the magnetic fields of active G stars.

We evaluated the frequency of flares with the total energy 10^{34} erg on active G stars: one flare every 5 years and one flare in 500 years for the stars with periods of about 3 days and about 12–15 days, respectively. This determines the range of the frequency of occurrence of such events for the young Sun. If flares of this energy could still be the result of evolution of the magnetic fields, the nature of the more powerful events should differ significantly from flares that occur in the present era. We evaluate the mass loss of the young Sun as much as 10^{-11} M_{Sun}/year, and the contribution of CME in this value was significantly higher than it is now.

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1. INTRODUCTION

Now there are many observations of individual phenomena of active processes on the Sun. In order to understand, what was the activity of the Sun in the past, when activity only was established, two basic approaches can be used. The first one is based on the theory of the angular momentum evolution and the dynamo. This enables to reveal the main factor of the activity evolution associated with braking of the rotation. More complicated is the question of the impact of the character of turbulent convection on the general properties of activity. The second approach uses a comparison of observational data on the activity of the Sun and other solar-type stars. On this path, ideas about the one-parameter gyrochronology linking the level of activity with the age of a star managed to develop (Mamajek and Hillenbrand, 2008). Observations of many active late-type stars with the space missions and with large optical telescopes fulfilled in frameworks of the Planet Search programs allowed advance in comparison of activity on stars of different ages and the Sun. Recent study of X-rays radiation versus rotation (Wright et al., 2011) and the further development of the gyrochronology based on a comparison of the chromospheric and coronal activity and revealing the role of magnetic fields at different scales in formation of activity (Katsova and Livshits, 2011; Katsova, 2012; Katsova et al., 2013).

So, we try to understand what one can conclude on the character of activity and its level on the young Sun in the era when solar-type activity only started to form. Now it is clear that there is a certain amount of stars with activity at the saturation level. Their L_X/L_{bol} ratio reaches 10^{-3} and does not depend on the rotation rate. This relates to stars with the period of rotation from 0.3 to 3 days. Such stars are not older than 600 Myr. Coronae of these stars are almost entirely filled with hot plasma with T about 10 MK, and the filling factor of spots can reach tens of percent. It can be assumed that the character of activity of these stars is quite different from the processes on the Sun. Here we will consider stars with rotation periods of 8–10 days and the slower ones. The level of their coronal activity is lower than the saturation, while both the chromospheric and

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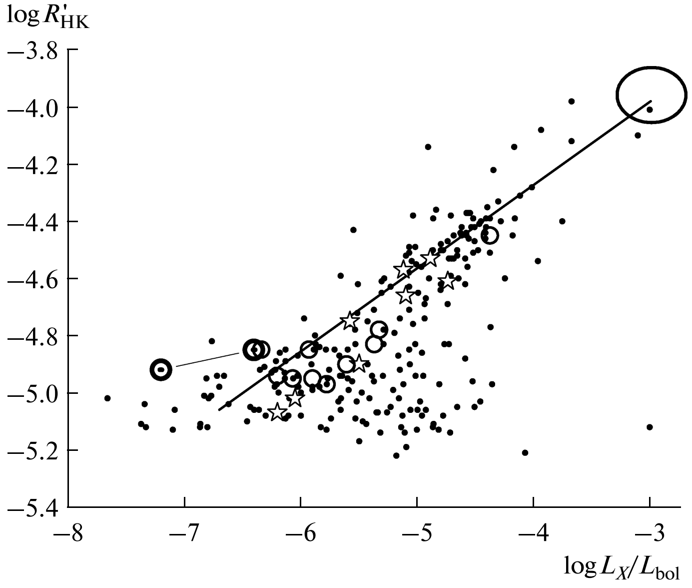

Fig. 1. The "chromosphere–corona" diagram for indices of the chromospheric and coronal activity for the late-type stars. The stars of the basic data set are marked as dots. Accordingly to the type of a cycle, the stars of group "Excellent" are marked as circles, the stars of "Good" group are indicated as asterisks; the Sun at the maximum and at the minimum is denoted its own sign, connected by the direct line. Oval is conditionally designated the positions of stars with the saturation of activity. The straight line corresponds to one-parametric gyrochronology.

coronal activity are quite high and there is no evidence of circumstellar disks and the predominance of the dipole magnetic field. Activity level of these stars is approaching characteristic level for Hyades stars with an age of about 600 Myr.

2. EVOLUTION OF SOLAR-LIKE ACTIVITY

Now it is firmly established that the level of activity of a star is determined by its age. After the stage of gravitational contraction there is a gradual braking of the star. This leads to a weakening of activity. Statistical study of the chromospheric and coronal activity of over 100 stars allowed to develop a one-parameter method of the gyrochronology for estimating the stellar age by the activity level (Mamajek and Hillebrandt, 2008). We have continued study this question at an expanded set of stars observed in the planet search programs. We built the diagram of the chromospheric and coronal activity indices, on which the main branch of stars is allocated linking the stars with low activity and the stars with saturation. The straight line in the diagram (Fig. 1) connects young stars aged hundred million years with the older stars, whose age is comparable to the solar one (4.5 Gyr) or more. This relationship differs little from that obtained earlier at the one-parameter gyrochronology. This means that axial rotation is indeed a major factor determining the activity level.

However, Fig. 1 shows that a large group of stars located below the line. These stars are characterized by the similar levels of chromospheric activity, while luminosities of their coronae vary within wide limits. For these stars, one-parametric gyrochronology is not longer applicable, and, apparently, there is an additional factor affecting activity. The relative fraction of G stars in the basic group is situated somewhat higher than that in the group of stars, several colder than the Sun, located in the diagram below the straight line. We assumed that the thickness of the convective zone can be an additional factor in the formation of activity (Katsova et al., 2013).

Really the Sun demonstrates phenomena associated with both the large-scale magnetic field (coronal holes, active longitudes), and with local fields (active regions, spots). The large-scale field, the quasi-biennial cycle is associated, apparently, with dynamo processes near the base of the convection zone, in the tachocline at a depth of about 0.3 R_{Sun}. On the other hand, according to the data of helioseismology, the grounds of sunspots are located just at 40000–50000 km below the photosphere, which indicates the relation between the local magnetic fields directly with the phenomena under the photosphere.

Processes near the base of the convection zone are affected differently on the formation of activity in selected two groups of stars, the hotter and cooler than the Sun. This agrees with the fact that active regions and flares, developing in local magnetic fields, are manifested more clearly on red dwarfs.

Note, however, that the separation into two branches of the evolution of activity occurs immediately after the stage of the gravitational contraction.

Even among the stars of the same age who are members of an open cluster, are both rapidly rotating, corresponding to a given age and objects, already slowed down their rotation. Thus, among the relatively young stars there are objects with periods ranging from several hours to 3–5 days, as well as stars with rotational periods from 5 days to 10–12 days.

Further we consider the stars whose convective zone has already formed, and the depth of its bottom, gradually diminishes, reaches the current level. This occurs in an era when the star reaches the age of about 1 Gyr. The rotation periods of these stars are 5–12 days and their age is of 1–2 Gyr. Effect of the thickness of the convective zone on the formation of activity is considered by Katsova and Livshits (2011), Katsova et al. (2013), and, of course, it is more significantly in these young stars than in the modern Sun.

3. STARS WITH THE ACTIVITY SIMILAR TO THE YOUNG SUN

What should be the star, whose activity corresponds to the processes that have occurred on the Sun in the age of 1–2 Gyr? It is clear that the relative area of spots on the surface of the young Sun considerably exceeded contemporary value even in the highest maximum of the cycle. Strongly spotted stars, most of them relating to the BY Dra-type stars, are located in a compact group on the "chromosphere–corona" diagram in the range of $\log R'_{\rm HK} = -4.5$ and $\log R_X = -4.5$.

The activity of the young Sun should be similar to the phenomena of the stars of this group. If on the contemporary Sun spots area is only 0.3% of the visible disk area in the maximum of the cycle, for the stars with the saturation of activity, the corresponding value reaches 10% or more. Analysis of features of activity for stars with the saturation of the activity was performed by Martinez-Arnaiz et al. (2011). These stars are characterized by the fast rotation with periods ranging from fractions of days to 8 days, and enhanced lithium abundance. The difference between the stars with saturation of the activity and less active stars is manifested also in the chromospheric emission. So, in Fig. 7 (left panel) in Martinez-Arnaiz et al. (2011) it is seen that depending on the H_α flux on the color index $B-V$ the stars begin to disperse, starting from the solar values of the color $B-V = 0.62$–0.64. This effect is reinforced for the redder (more cold) stars and it is maximal for K and M stars. Clearly, the star with the saturated activity located on the upper branch, are younger than the others. It follows that the dependence of the activity–age for the G stars on the age is weaker than for the K stars. Because we are interested in the activity of a young G stars, we can determine the activity indices of such a star even at large uncertainties in estimating of the age. Thus, we can estimate these indices to the Sun in an era when its age was 1–2 Gyr.

The location, corresponding to the young Sun, on the "chromosphere–corona" diagram is situated only slightly below of the center where the BY Dra-type stars are located. Here there are, in particular, such known active stars as HD 1835 (BE Cet), HD 20630 (κ^1 Cet) and HD 152391 (V 2292 Oph). The relative spot area of the G stars, BE Cet, reaches 3.3% (Alekseev, 2001). The G7 star, V 2292 Oph, is characterized by the faster rotation from the other stars with the *Excellent* cycles. In recent years, it is noted that the cyclic activity with a period of about 11 years became less regular in this star. This allows us to consider it as representative of the stars with the *Good* cycle. The rotation periods of these stars are 8, 9 and 11 days, respectively.

For the G dwarfs rotating 2–3 times faster than the contemporary Sun, the rotational modulation of the optical continuum radiation is clearly pronounced. It is studied in details for late-type stars younger than the Sun by Messina et al. (2001, 2003). As it is seen in Fig. 3 in Messina et al. (2003), the amplitude of the rotational modulation exceeds the variation of the total solar irradiance by 1–2 orders of the magnitude, and it is related not only with an increase of the spot area, but also with their concentration to definite active longitudes. Along the information about magnetic fields of these stars (see below), this means that the large-scale magnetic field up to the dipole affects the formation of activity. For the young G stars aged about 1 Gyr with the rotational period around 10 days, this impact is manifested not so clear as for the stars of the same mass with the age less than 100 Myr and the periods from several hours to about 5 days, that have not come down to the main sequence. Note that EK Dra, often used as an example of the young Sun (with the rotation period of about 3 days) refers to objects approaching the main sequence. Despite the large relative spot area over 20%, the dipole component of the magnetic field dominates the measured quantity of the field.

Thus, the general nature of activity of the young Sun differs from that we see in the maximum of cycles during XX and XXI centuries. Spots covered the solar area of about one order of magnitude greater than it is now. The soft X-ray luminosity was hundreds of times higher than at present. The fluxes of solar wind and their changes with the rotation period of the young Sun were much stronger. The character of non-stationary processes in the energy and duration of events differed significantly also. The activity of the young Sun is close to the phenomena of the stars HD 1835 (BE Cet) and HD 152391 (V 2292 Oph) with the rotation periods 8 and 11 days, respectively.

4. MAGNETIC FIELDS ON G STARS

Until now, there were only a few measurements of magnetic fields on low-mass dwarfs. As for the Sun, the field strength along the line of sight is determined directly from the spectra, comprising one or more magnetically sensitive lines, especially in the optical and near IR ranges. Such a study of the Zeeman effect in the late-type stars could reveal the magnetic field strength of 1–3 kG in spots covering up to 10% of stellar surface. The signal varies with the phase of the axial rotation period. This is studied fairly well for only several stars. The corresponding measurements are presented, for instance, in papers by Valenti et al. (1995), Tarasova et al. (2001), in particular, for ξ Boo A (G8 V) and the K stars, ε Eri, 61 Cyg A, and σ Dra. For the most active stars with rotational periods of 6 and 12 days the observations are consistent with a model in which the spots with the magnetic field strength of about 1.5 kG cover approximately 20 and 10% of the area respectively. Stars with rotation periods of about 30 days the magnetic fields in spots reach 1–2 kG, and their area does not exceed 2%.

These results agree well with modern view on the stellar magnetic fields. First, changes in the magnetic field strength with the phase of axial rotation together with spectral data provide an opportunity to simulate the distribution of inhomogeneities over the stellar surface. This method the Zeeman Doppler mapping allows in the first approximation to separate the contributions of spots and large-scale magnetic field. Here the basic laws such as the dependence of the mean surface field on the axial rotation rate and the overall level of activity star are retained (Petit et al., 2008).

As a result, we conclude that the general nature of the magnetic fields on G and K stars, is similar that observed on the Sun now. Namely, there is a large-scale magnetic field, most clearly manifested in the polar regions and the local fields at low latitudes. Contribution of the magnetic fields of different scales in the average value changes over several years and depends on the orientation of the rotation axis and the dipole axis with respect to the line of sight.

Second, new data on the magnetic fields of the solar-type stars recently obtained in the framework of "*Bcool Collaboration*" (Marsden et al., 2013). The spectropolarimetric observations of 170 late-type stars were carried out with the large telescopes. For magnetic field measurements from 5000 to 11000 spectral lines were used simultaneously, which allowed to measure accurately enough the value of the longitudinal component of the magnetic fields. The mean surface longitudinal magnetic field B_l was detected for about 40% of the "Bcool" sample stars. This value represents the B_l signal averaged over all observations of the star. Such spectroscopic observations give possibility also to determine both the fundamental parameters of these stars, and level of their chromospheric activity. For the population of K-dwarfs, the authors give the average values of the mean $|B_l|$ that found to be higher (5.7 G) than mean $|B_l|$ measured for the G dwarfs (3.2 G) and the F dwarfs (3.3 G).

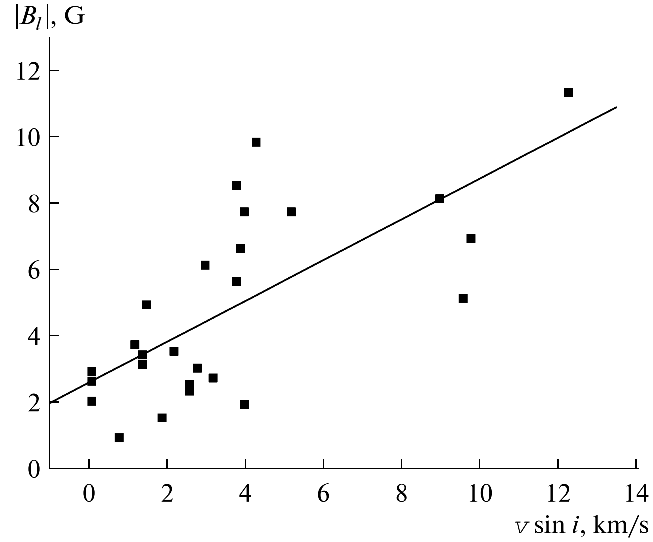

Fig. 2. Dependence of the mean module of the longitudinal magnetic field on the rotational velocity $v\sin i$ for the stars with the ages of 1–2 Gyr (see the text).

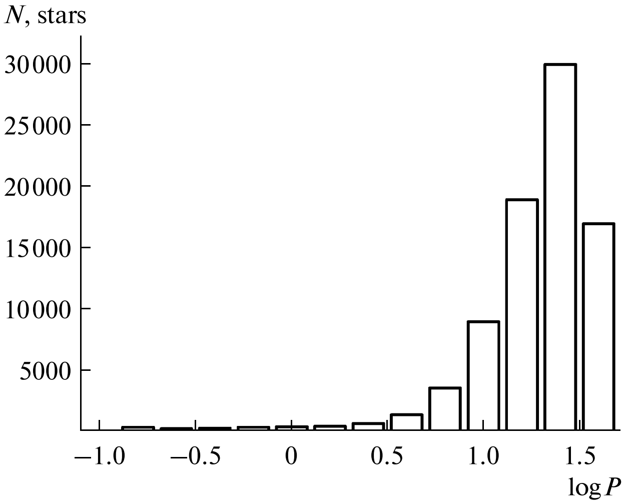

Fig. 3. Distribution of the G main sequence stars observed with the Kepler mission over the axial rotational periods.

We analyzed briefly these observations for only G stars in order to estimate approximately the magnetic field strength for the young Sun. We chose all G stars with values B_l, exceeding 3σ, from Table 3 of Marsden et al. (2013). From the list, we excluded some of rapidly rotating and hence young stars with strong magnetic fields. Thus, the final list includes 28 G stars whose rotation periods more than 5.0 days (from the approximate evaluation of the rotational periods based on the chromospheric indices of Table 5 in Marsden et al., 2013).

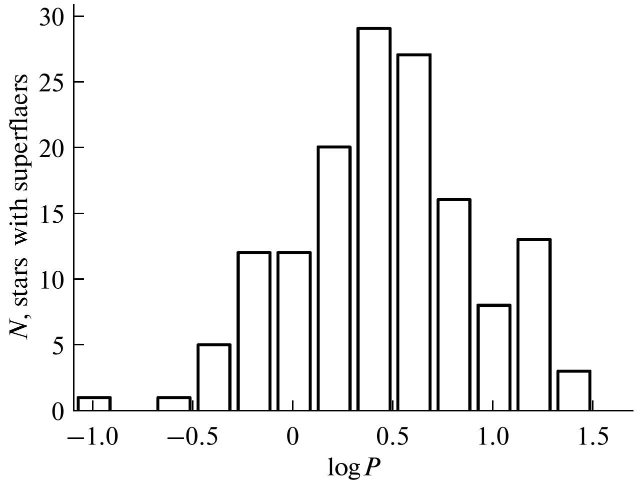

Fig. 4. Distribution of the G stars where superflares were registered on the rotation periods.

The result is presented in Fig. 2. Values of modules of the field, $|B_l|$, for the two stars, ξ Boo A and 61 UMa, exceed significantly those, typical for stars with such rotation periods. As noted in the Marsden et al. (2013), it is most likely due to the uncertainty of the angle of inclination of the axis of rotation of the star to the line of sight. Without both of these stars, the correlation coefficient values $|B_l|$ and $v\sin i$ is greater than 0.70.

So, if we exclude the stars, where the field is not reliably registered, as well as a few stars with very strong magnetic fields, we can get the average value of the modulus of the field $|B_l|$, equal to 4.72 ± 0.53 G for the G stars. Dependence corresponding to Fig. 2 reflects the weakening of the mean field of the stars during its braking, i.e. with increasing age. The obtained average value of the field corresponds to the rotation speed of about 4 km/s, twice faster than the rotation of the modern Sun. This allows us to adopt such a value of the field as an average value for the G star with a rotation period of about 10 days, which corresponds to the age of 1–2 Gyr.

Compare this value with the data on the general magnetic field of the Sun as a star. Values averaged over the Carrington turnover near the maximum of the cycle do not exceed 0.5 G, see, for example, Kotov et al. (1999) for data on magnetic field of the Sun as star in 1991. Thus, the average magnetic field strength of young G stars, at least an order of magnitude higher than the maximal Sun in the modern era.

Note that this estimate is supported by the fact that the magnitude $|B_l|$ for stars whose parameters are most similar to those of the young Sun, equal to 8.5 G for V 2292 Oph and 7.7 G for κ^1 Cet (on other data of this star $|B_l|$ = 7.0 do (Nascimento et al., 2013)). This agrees with the above general conclusion.

Now there is information on the structure of the large-scale magnetic fields of late-type stars. In particular, it was found that the slowly rotating stars have magnetic fields with the same structure as that on the Sun, which are changed regularly during the 22-year magnetic cycle. In other words, the global dipole exists virtually all the time, and only during polarity reversal the magnetic equator shifts in longitude, which can be regarded as a manifestation of a large-scale toroidal component. Active regions are located rather chaotically, active longitudes are allocated poorly, and toroidal fields are characterized by comparatively small scales (local fields). At the same time the large-scale toroidal component clearly pronounced on the G stars with rotation periods less than 12 days (Petit et al., 2008). Although it prevails over large-scale poloidal magnetic fields, the difference of the magnetic field strength is small. So far it is difficult to relate these conclusions with new data on the spots on the rapidly rotating G stars.

5. SUPERFLARES ON G DWARF STARS

Generally speaking, until recently, data on flares on G dwarfs (except the Sun) were practically absent. The Kepler mission was launched on March 7, 2009 and observations were made of more than 0.5 million stars. These data allow us to study the processes in stars with similar to the Sun characteristics. A special study of G dwarfs was published in Nature (Maehara et al., 2012), where results of the detection of large flares were presented. The V band monitoring was carried out in two modes, with a time resolution of about 1 and 30 min, and so far the main conclusions obtained from the data set with a lower resolution. The energy of "white-light" stellar flares converted into the bolometric magnitude in the blackbody radiation approximation. Unexpectedly superflares with the total energy in the range from 10^{33} to 10^{36} ergs were detected.

We conducted a preliminary analysis of observations reported in the table. S1 of Appendix to Maehara et al. (2012). 625 flares were recorded on 148 dwarfs from 82806 main sequence G stars. Figure 3 shows the distribution of all of these stars on the periods of the axial rotation. It can be seen that the majority of stars studied here rotate with periods of 20–30 days, i.e. about like the modern Sun.

Distributions of those stars where flares were registered and the number of such non-stationary processes on the rotation periods are shown in Fig. 4 and Fig. 5. It is seen that detectable now powerful flares on G stars are very rare events. The maximum of the distribution of the number of stars with superflares achieved at the rotation period of about 3 days, and it refers to the group of stars with periods from several hours to 6–8 days. Such a representation allows us to conclude that super-flare occur more frequently on the dwarfs with rotation periods of about 3 days.

Shapes of the distributions of the number of stars with flares on the rotation period and the number of superflares are similar because they relate to events and objects on them. Note that the ratio of the maximal values to the average ones over the distribution for the number of flares (Fig. 5) is greater than that for the amount of stars (Fig. 4). This means that more than a single flare (from 3 to 20 events) for the same period of time was registered on the stars with the rotation periods of about 3 days and about 15 days as well. Otherwise, flare activity is increased in G stars with such periods of rotation. Note that Maehara et al. (2012) showed that the frequency of superflares is slightly higher for the cold G stars than hotter ones.

The Kepler data allow us to determine the frequency of large flares with energy above 10^{33} erg. However, both results by Maehara et al. (2012) and our analysis for energies 10^{33}–10^{34} ergs is based on dozens of events, and statistically not well founded. Reliable data are presented by Shibayama et al. (2012): the frequency of such superflares for two groups of stars with rotational periods of about 3 and 10 days is about 2×10^{-33} and 2×10^{-37} erg^{-1} star^{-1} year^{-1}, respectively. Hence the number of flares to the total energy in 10^{34} erg per one active star per year is estimated at 0.2—one flare every 5 years for stars with the period of about 3 days and 0.002—one flare every 500 years for stars with periods 12–15 days.

Thus, very powerful flares occur really on some fairly young G stars. Two maxima in the distributions in Figs. 4 and 5 are most probably related to the different ages of objects and the structure of the magnetic fields. It is not clear why appears deficit of stars with periods around 10 days and number of flares on them: either here the physical differences of the mechanisms of formation of activity are manifested or this is an effect of selection.

Let us briefly discuss the question of the upper limit of the total energy flares that can develop on a given G main-sequence star. This problem has been studied most fully to the Sun. So in 1995, we have defined the energy of currents arising above sunspots (Livshits, 1995). It was formulated and solved the following problem: to evaluate the energy of the potential field in the layer, which is located above the vertical dipole and compare it with the case, when this region is bounded by a highly conductive surface that prevent to the penetration of the magnetic field upwards. It was shown that such screening leads to an increase twice in the energy of the field in a thin flat layer. The energy of surface ring current, i.e. the difference between the energy of the field in the presence of a screen or without it has the form

$$\Delta W = 3/16 B^2 a^3 (d/a), \qquad (1)$$

where B is the field in the center of a spot, a is the depth of submersion of the dipole beneath the photosphere, d is thickness of the layer in the chromosphere. When the field strength in the photosphere at the center of the spot $B = 3000$ G, the depth of submersion of a vertical dipole $a = 15000$ km and thickness $d = 2000$ km, we obtain the energy of currents $W = 1.9 \times 10^{32}$ erg. Note that the total current reaches 10^{12} A that is often estimated from observations.

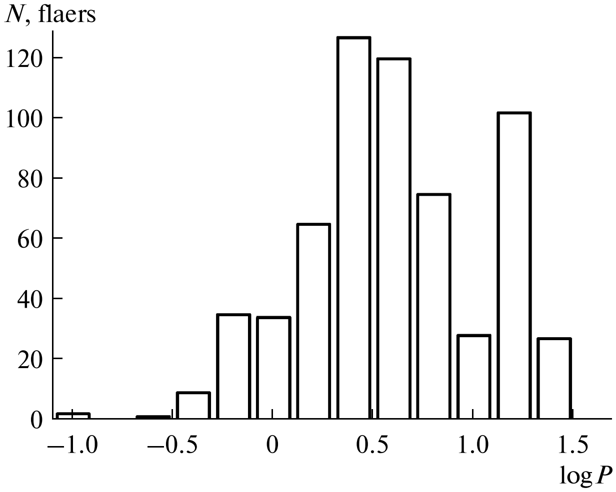

Fig. 5. Distribution of the number of flares with the energies $>10^{33}$ erg depending on the rotational periods.

Even such a simple analysis shows that the currents occurring above a large single spot on the Sun can ensure the development of a flare with this energy. This is consistent with the observations of the Sun in the past 5–10 cycles.

Currently, a similar approach has been developed in numerous papers on the extrapolation of the magnetic fields from the photosphere to the corona. The most important is taking into account the fact that the ratio of the gas pressure to the magnetic pressure becomes significantly less than 1 when passing from the photosphere of the active region into the outer layers. The magnetic field above the photosphere can be regarded as force-free field, currents flow in thin filaments, which are located in the active region of the polarity inversion line. The difference between the total E and potential energy E_{pot} in this volume, here the value of W, is now called the free energy of $E_{\text{f}} = E - E_{\text{pot}}$.

The value of the free energy can be found from observations of the full vector of the magnetic field and the subsequent approximation of the field into the corona. If the assumption is valid that the magnetic fields decays rapidly with distance from the center of the active region and the height, the observations of the full vector of the magnetic field give possibility to evaluate the free energy even without extrapolation of the field into the corona using the approximate expression

$$E_f = E - E_{pot} = \frac{R}{8\pi} \int_{S_b} (B_{t,\,pot}^2 - B_t^2) ds, \quad (2)$$

where $B_{t,pot}$ and B_t are the tangential components of the potential and full fields in the photosphere, S_b is the active region area (Livshits et al., 2014). Thus, for each active region on the Sun can be found the absolute limit of the total energy of flares that may occur there. Comparison with observations shows that up to 15% of the free energy of the active region may be expended for every powerful flare. We shall assume that for the powerful center of activity, the value of the free energy is equal to 2×10^{33} erg, and there may occur the flares with the total energy of 3×10^{32} erg.

For slowly rotating G stars, the upper limit of the total energy of flares should be close to the solar values due to similar structure of the magnetic fields. The situation varies on going to rapidly rotating stars. The average magnetic field strengths exceed by about an order of magnitude those observed on the Sun. Already from the expressions (1–2) it implies that the magnetic energy and, consequently, the value of ΔW varies by 2 orders of magnitude. We can say that the free energy varies also by about 100 times in an isolated active region on a rapidly rotating star. This enables to occur super-flares with the total energy in 10^{34} ergs on these stars.

We emphasize that the large average magnetic field strength in the rapidly rotating star is associated not so much with the stronger fields in the center of the spots, but with an increase in the relative spot area—filling factor. This may affect the frequency of flares and the total energy release during the flares on the whole the star for a certain period of time, but does not increase the total energy of the individual flare. Therefore superflare detected cannot be a complete analogue of powerful solar flares, and phenomena with energies greater than 10^{34} erg are associated with drastically another process rather than the accumulation of the free energy in the chromosphere and its subsequent release. Here we can enumerate three possibilities. First, some rare episodes in the Sun indicate the development of non-stationary processes occurring simultaneously in several large groups of spots. Examples can be the periods with enormous enhancement of flare activity, for instance, in October 2003 (Chertok and Grechnev, 2005), partly in August 1972 and etc. Second, the evolution of large-scale toroidal components perhaps associated with the concentration of centers of powerful activity at a fixed longitude may help to strengthen the power of events related to the global restructuring of the corona of the entire star. The third possibility, hypothetical, ejection of a rope, formed deep beneath the photosphere, can be regarded as a superflare. General observational manifestation of these mechanisms should be significant Doppler velocities of the ejected plasma and weakening in the star's brightness in EUV spectral region (the solar analogue of this phenomenon is huge dimmings).

6. THE MASS LOSS BY THE YOUNG SUN

In the contemporary era, the mass loss of the Sun is 3×10^{-13} M_{Sun}/year and is associated mainly with the quasi-steady plasma outflow from the corona. What about the mass loss by young Sun? The basic information is contained in the soft X-ray and EUV-observations of stellar coronae. The X-ray luminosity of the modern Sun is much less as compared with other active late-type stars. However, the hot coronal gas is concentrated in fairly low loops. The low-speed wind stream is formed near the top of the loop, in the cusp region, and it is enhanced slightly with an increase of the mass of the hot coronal plasma. Thus, even if the soft X-ray radiation of the G star is approaching the saturation level, i.e. increases by 3–4 orders of magnitude as compared with the Sun, the rate of outflow of matter in the streamers does not increase by more than one order of magnitude. The high-speed flow from regions with open magnetic configuration is also increasing compared to the current Sun. However, the high-speed wind of the young Sun must be amplified becouse the plasma density at the base coronal hole (or the polar region) increases, while the outflow is formed at higher coronal levels. Therefore, as on the Sun at the present, the contribution of the outflow with 300–500 km and 500–1000 km/s to the quasi-stationary mass loss is comparable. Generally speaking, the MHD calculations confirm such an assessment, if we consider the star with age no younger than 600–800 Myr (Cohen and Drake, 2014). The estimate of quasi-stationary mass loss of the young Sun of 10^{-11} M_{Sun}/yr seems reasonable.

The main difference between the formation of the wind in that era and in the present time lies in the fact that dynamic processes happened then much more often. Recent observations show that quite powerful flare with the energy of about 10^{31} erg is accompanied, as a rule, by coronal mass ejections (CMEs), about 10^{16} g. For example, we estimate the mass loss due to CME for the κ^1 Cet with the rotational period of about 9 days, which can be regarded as an analog of the young Sun. Thus, for κ^1 Cet, the flare frequency with an energy of about 10^{34} erg is about by 2 orders of higher than the corresponding quantity for the majority of most active solar-type stars. If we extrapolate this value to the energy of 10^{31} erg under the same law that in Fig. 9 in Shibayama et al. (2013) we obtain the frequency of such events 3×10^{-26} erg^{-1} star^{-1} year^{-1}. This means that this star should undergo 2×10^5 such events per year. This corresponds to the mass loss associated with CMEs, 10^{-12} M_{Sun}/year. Despite the fact that this value is only 10% of the possible rate of quasi-stationary outflow of the young Sun, the contribution of

CME in the mass loss rate of the young Sun was significantly higher than at the present day.

Thus, the total mass loss of the young Sun was high, about 10^{-11} M_{Sun}/year. If this rate is maintained for about a billion years, it will lead to a decrease in the mass of the Sun by 1%. This does not affect the bolometric luminosity of the Sun, but maintains a high rate of decrease of the angular momentum. In this era, fundamental changes in the character of activity relating to the configuration of the magnetic field undergoing, under certain conditions, the cycle begins to form, etc.

7. CONCLUSIONS

The solar activity is caused by interaction of the magnetic fields of different scales. What about solar activity in the period when it was just starting? New registration of the magnetic fields and information on the character of activity in different atmospheric layers of the G main-sequence stars are a base for the further consideration. First of all, we considered the question of the age and/or the velocity of the axial rotation of the young Sun. We were based our results on the evolution of solar-type activity and found that the quasi-stationary activity formed during the age of about 1–2 Gyr, when the rotation was braked, and the axial rotation period became to be close to 10 days.

We have identified the activity levels of the chromosphere and corona of the young Sun. Activity on the young Sun is closest to the processes in G stars HD 152391 (V2292 Oph) and HD 1835 (BE Cet) with the rotational periods of 11 and 8 days, respectively. The total spot area was of about 2 orders of magnitude higher than the current value at the maximum, the activity levels of the chromosphere and corona are quite high, close to the Hyades level, but did not reach the saturation level. The amplitude and duration of the cycle had undergone only minor changes since then. The mass loss of the young Sun is estimated to be 10^{-11} M_{Sun}/year, with the contribution of CME's in this value is significantly greater than in the modern era.

We analyzed the new detection of longitudinal magnetic fields and the distribution of toroidal and poloidal fields on G main-sequence stars. We found that the mean longitudinal field of active G stars is about one order of magnitudes higher than the average daily field Sun as a star, such as a maximum of the 21th cycle. Furthermore, it is important that the existence of large-scale toroidal magnetic field in these stars is revealed.

This has helped to analyze data on superflare on the G stars detected by the Kepler mission. We have defined the upper limit of the energy of the flares that may occur in the magnetic fields of active G stars. We evaluated the frequency of flares with the total energy in 10^{34} erg on active G stars: one flare every 5 years and one flare in 500 years for the stars with periods of about 3 days and about 12–15 days, respectively. This determines the range of the frequency of occurrence of such events for of the young Sun.

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