The Evolution of the Solar-Stellar Activity

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ARTICLE INFO

Keywords:
Solar-stellar connections
The Young Sun: activity
The Sun: activity
stars: activity
stars: flares

ABSTRACT

We present a brief review of observational results contributing to modern ideas on the evolution of stellar activity. Basic laws, derived for both rotation-age and activity-rotation relationships, allow us to trace how the activity of low-mass stars changes with age during their stay on the main sequence. We focus on the evolution of the activity properties of stars that could be analogs of the young Sun. Our study includes joint consideration of different tracers of activity, rotation and magnetic fields of Sun-like stars of various ages. We identify rotation periods, when the saturated regime of activity changes to the unsaturated mode, when the solar-type activity is formed: for G- and K-type stars, they are 1.1 and 3.3 days, respectively. This corresponds to an age interval of about 0.2 – 0.6 Gyr, when regular sunspot cycle began to be established on the early Sun. We discuss properties of the coronal and chromospheric activity in young Suns. Our evaluation of the EUV-fluxes in the spectral range of 1350 – 1750 Å shows that the far-UV radiation of the early Sun was a factor of 7 times more intense than that of the present-day Sun, and twice higher when the regular sunspot cycle was established. For the young Sun, we can estimate the possible mass loss rate associated with quasi-steady outflow as $10^{-12} M_\odot$/yr. The results of observations of the largest flares on solar-type stars and the Sun during the past almost 60 years. Magnetic activity can be traced in all the layers of the stellar atmosphere and on various timescales (e.g. Wilson 1978; Baliunas et al. 1995; Güdel et al. 1997; Lockwood et al. 2007). These stars possess a radiative core and an outer convection zone. The magnetic field is generated through the interaction between convection and axial rotation creating magnetic fields, and thereby the whole set of magnetic activity phenomena, best studied on the Sun due to its proximity.

Observations of different tracers of stellar activity showed that the main factor determining the activity level is the axial rotation of a star. Skumanich (1972) was the first who discovered a specific rotational braking law for solar-type stars in the Pleiades, Ursa Major, and Hyades open clusters and the Sun from an analysis of the time-scales for Ca II emission and the relative magnetic field strength. Then this law (Fig.1 in Skumanich 1972) implies that the average surface (dynamo) field is proportional to $\propto t^{-1/2}$. This rotational braking is caused by the torque provided by the magnetized stellar wind, outflowing along magnetic field lines, which is able to efficiently remove the angular momentum of the star.

1. Introduction

A wide variety of magnetic activity phenomena in different spectral ranges have been observed in stars with masses $< 1.5 M_\odot$ and effective temperatures $\leq 6500 K$ over the past almost 60 years. Magnetic activity can be traced in all the layers of the stellar atmosphere and on various timescales (e.g. Wilson 1978; Baliunas et al. 1995; Güdel et al. 1997; Lockwood et al. 2007). These stars possess a radiative core and an outer convection zone. The magnetic field is generated there via a dynamo mechanism whose properties depend on the stellar interior structure. The interaction between convection and axial rotation creates magnetic fields, and thereby the whole set of magnetic activity phenomena, best studied on the Sun due to its proximity.

Observations of different tracers of stellar activity showed that the main factor determining the activity level is the axial rotation of a star. Skumanich (1972) was the first who discovered a specific rotational braking law for solar-type stars in the Pleiades, Ursa Major, and Hyades open clusters and the Sun from an analysis of the time-scales for Ca II emission and the relative magnetic field strength. Then this law (Fig.1 in Skumanich 1972) implies that the average surface (dynamo) field is proportional to $\propto t^{-1/2}$. This rotational braking is caused by the torque provided by the magnetized stellar wind, outflowing along magnetic field lines, which is able to efficiently remove the angular momentum of the star.

This relation, called the "Skumanich law", has served as the basis of the gyrochronology method (Barnes, 2003), which yields age estimates based on rotation observations. As it is known, an intensity of the Ca II K line on the Sun varies linearly with surface magnetic field strength (Frazier, 1970), therefore the stellar Ca II emission can be identified with the (average) surface magnetic field. Later on Schrijver et al. (1989) found a ratio between the chromospheric Ca II emission and the absolute value of the mean magnetic flux densities: the Ca II HK flux is proportional to $\propto fB^{0.5}$ (where $f$ is an area filling factor and $B$ is the intrinsic field strength). Then this law (Fig.1 in Skumanich 1972) implies that the average surface (dynamo) field is proportional to the rotational velocity and decays as the inverse square root of the time while the star is located on the main sequence.

This relationship between the magnetic field and age could be used as a way to estimate stellar ages ("magnetochronology"), although it would not provide a better precision than most of currently adopted age-dating methods (Barnes, 2003). They empirically found that the unsigned average large-scale surface field $<|B_v|>$ is related to age as $\propto t^{0.655\pm0.045}$. This relationship between the magnetic field and age could be used as a way to estimate stellar ages ("magnetochronology"), although it would not provide a better precision than most of currently adopted age-dating methods. Results by Rosen et al. (2016) showed a significant decrease in the magnetic field strength and energy as the stellar age increases from 100 Myr to 250 Myr, while there is no significant age dependence of the mean magnetic field strength for stars with ages 250 – 650 Myr. The spread in the mean field strength between different stars is comparable to the scatter between different observations of individual stars. They applied a modern Zeeman-Doppler imaging (ZDI) code in order to reconstruct the magnetic topology of all stars (see

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also Kochukhov et al. (2017)).

Note that the ZDI measured field is a small fraction of the total magnetic field, and a fraction which varies with rotation. Now Kochukhov et al. (2020) developed a new magnetic field diagnostic method based on relative Zeeman intensification of optical atomic lines with different magnetic sensitivity. They found that the average magnetic field strength $\mathcal{B}_f$ drops from $1.3 - 2.0 \text{ kG}$ in stars younger than about 120 Myr to $0.2 - 0.8 \text{ kG}$ in older stars. These results suggest that magnetic regions have roughly the same local field strength $B \approx 3.2 \text{ kG}$ in all stars, with the filling factor $f$ of these regions systematically increasing with stellar activity. Comparison of these results with the spectropolarimetric analyses of global magnetic fields in the same young solar analogues shows that ZDI recovers about 1% of the total magnetic field energy in the most active stars. These new data are very important for understanding of different evolutionary phases of the solar-like magnetic dynamo and can be used to estimate magnetic characteristics of the Sun during the first $\sim 1 \text{ Gyr}$ of its life.

The rotation periods of young stars in star formation regions in the stage of gravitational contraction were determined directly from observations of the rotational modulation of their photometry. The rotation periods of young stars with masses from 0.8 to $1.2 \, M_\odot$ were found to vary from 7 days to about $< 1 \text{ day}$ as the age varied from 1 to 70 Myr (Fig. 7 in Messina et al., 2011), i.e. rotation accelerated as the star approached the main sequence. The subsequent braking of rotation associated with the angular momentum loss due to the magnetized stellar wind occurs over significantly larger time scales of billions of years.

Gyrochronology is based on the observation that main-sequence stars spin down as they age (Barnes, 2003), and thus if correctly calibrated, rotation can act as a reliable determinant of their ages. To calibrate gyrochronology, the relationship between rotation period and age must be determined for cool stars of different masses, which is best accomplished with rotation period measurements for stars in open clusters with well-known ages (Meibom et al., 2015). Then gyrochronology may be a more precise clock than other techniques like asteroseismology and isochronal methods for cool main-sequence stars.

Observations of rotation of open cluster members of different ages revealed two populations: the fast rotating stars and the slower rotators. One of conclusions by Barnes’ PhD thesis (Barnes, 1998) was: the existence of the ultra-fast rotators implies that angular momentum loss from young stars is inconsistent with a Skumanich-type slowdown. It may be interpreted either as evidence for magnetic saturation at high rotation rates or for a different magnetic field configuration in young stars, before the Skumanich spindown phase. Moreover, with increasing age, the number of rapidly rotating stars decreased (Barnes, 2003). Such coexistence both fast and slow rotators among young low-mass stars was discovered later on during the Kepler mission data for more than 34 000 stars (McQuillan et al., 2014).

Later, Mamajek and Hillenbrandt (2008) proposed a way for improved age estimation for solar-type dwarfs using activity-rotation diagnostics. Their new activity-age calibration has typical age precision of $\sim 0.2$ dex for these normal F7–K2 dwarfs aged between the Hyades and the Sun ($\sim 0.6 - 4.5 \text{ Gyr}$). They showed that the coronal activity index as measured through the $R_X = L_X/L_{bol}$(the X-ray to the bolometric luminosity ratio) has nearly the same age- and rotation-inferring capability as the analogous chromospheric activity index measured through the $R_{HK} = L_{HK}/L_{bol}$(the chromospheric to the total bolometric luminosity ratio). It is calculated from the so-called S-index, a band ratio measurement of the Ca II H and K emission line strength at 3933 Å and 3968 Å, respectively, from which the underlying stellar photospheric contribution is then subtracted. Physically, variability in these lines is a time manifestation of surface magnetic inhomogeneities, and is often used as a proxy for the stellar magnetic activity (Baliunas et al., 1996).

Thus, by systematic observations of different activity indices for stars of various ages, the gyrochronology method (rotation-age dependence) was developed, making it possible to explore the evolution of activity of a star over its life on the main sequence.

2. Results

2.1. A scenario of the evolution of stellar activity

Available observations permit us to compare the main activity indices of large numbers of stars of various ages (rotation rates) and to understand how activity evolves. A major expansion in the exploration of the evolution of stellar activity began through use of data from the California, Carnegie and Magellan planet search programs (Wright et al., 2004; Arriagada, 2011). They provided data on the chromospheric activity (index $R_{HK}$) for more than 1300 northern and southern stars obtained as a by-product of these projects.

The X-ray data for coronae of these stars (the coronal activity index $R_X$) were derived from observations in the soft X-rays carried out with the ROSAT and XMM-Newton (for instance, Hünsch et al. 1999; Schmitt and Lieftse 2004), and for a few dozen stars from results by Poppenhaeger et al. (2010, 2011). This dataset can be used to study the location of solar activity among activity phenomena occurring on other late-type stars, and to trace the evolution of solar-like activity from ages of about 100 Myr to $> 6 \text{ Gyr}$.

Considering the indices of coronal and chromospheric activity together, we proposed the “chromosphere-corona” diagram: $(R_{HK}$ versus $R_X$) which allowed us to compare a level of the solar activity with that of other stars, and to analyze how these parameters change (Katsova and Livshits, 2011; Katsova, 2012). This diagram is presented in Fig.1; it includes over 250 stars from several observational programs.
Besides stars from the Mt Wilson HK-Project with chromospheric starspots cycles determined as Excellent and Good (Baliunas et al., 1995) and stars from the above mentioned exoplanet search program, we added stars with detectable lithium abundances (López-Santiago et al., 2010; Maldonado et al., 2010; Mishenina et al., 2012). The lithium data, including our own observations, were added because the Li I 6708 Å line is known as an indicator of stellar age and, consequently, the activity level (Skumanich, 1972). The lithium abundance is sensitive to the temperature near the bottom of the convection zone: lithium is efficiently depleted when this temperature reaches about 2-2.5 MK. Physical conditions in these deep layers determine the properties of the dynamo and, in general, the features of the magnetic field generation. We discovered the correlations between the Li abundances, rotational velocities and the level of the chromospheric activity for F-, G- and K-type main-sequence stars and found that it was tighter for the stars slightly cooler than the Sun, with the effective temperatures $T_{\text{eff}} > 5200$ K. For highly active stars, we confirmed that both the Li abundance and the activity level are determined by the age-dependent rotation rate (Mishenina et al., 2012). The stars with detectable Li in the "chromosphere-corona" diagram cover a wide range of the activity indices up to the saturation level. Apparently, differences in behavior of the Li abundances in the stars of various activity levels could be associated with the changes of a relative contribution of the small-scale (local) and large-scale magnetic fields in generating the activity (Katsova et al., 2013). In particular, this is the case when the Li excess can be evidence for higher stellar activity associated with very powerful stellar flares (see, for example, results by Livshits (1997); Livingston et al. (1997); Ramaty et al. (2000) for solar flares, and those by Montes and Ramsey (1998) for a stellar flare).

The green straight line corresponds to the linear regression between the coronal and chromospheric indices for all intervals of their values (the ratio for the one-parameter gyrochronology) by Mamajek and Hillenbrandt (2008):

$$
\log R'_{\text{HK}} = -4.54 + 0.289(\log R_X + 4.92).
$$

These authors used the updated ages of well-studied nearby open clusters (e.g., alpha Perseus, Pleiades, Hyades) and considered the rotation-activity-age relation. Their new activity-age calibration has typical age precision of ~ 0.2 dex for normal solar-type dwarfs aged between the Hyades and the Sun (~ 0.6 – 4.5 Gyr). This allowed us to determine a region on this diagram where the youngest stars with saturated activity are located, the approximate location of fast rotators with ages $< 0.5$ Gyr, $\log R'_{\text{HK}} \sim -4.0$ and rotation periods $P_{\text{rot}} < 1$ d), the level of the young Sun in the age of $\leq 1$ Gyr ($\log R'_{\text{HK}} \sim -4.5$, $P_{\text{rot}}$ around 7 – 10 d), and a place of the contemporary Sun in the age 4.5 Gyr ($\log R'_{\text{HK}} \sim -4.88$, $P_{\text{rot}} = 25$ d) as well.

A few features in the behavior of different groups of stars should be noted. For example, the chromospheric activity of the Sun is clearly higher than that for the vast majority of stars in the solar vicinity (e.g. the same ages), while the solar corona is much weaker even at the maximum of the sunspot cycle as compared to coronae of other main-sequence stars. The stars with well-defined cycles situate along the line corresponding to the one-parameter gyrochronology by Mamajek and Hillenbrandt (2008). Their chromospheric and coronal activity decreases almost simultaneously. This kind of activity follows Skumanich’ law and relates to solar-type activity that implies a starspot cycle formation.

From the other side, stars with the detectable Li, which are more active and younger than others among these objects, deviate from this line: there is also a significant group of stars for which the chromospheric activity diminishes, while their coronal radiation spans a wide range or remains quite intensive. Note that a wide spread in $R'_{\text{HK}}$ for a given $R_X$ for low $R_X$ is partly because $R'_{\text{HK}}$ is uncalibrated for metallicity (the iron abundance), while $R_X$ usually is (Saar and Testa, 2012).

The upper part of this diagram (the grey ellipse) indicates direction to a region where the youngest, fast-rotators with very high activity are located. These stars are characterized by saturated activity and even supersaturated regimes for the fastest rotators. This diagram shows possible paths of the evolution of solar-type activity: decay of the chromospheric and coronal activity can occur by different ways. Moreover, in fact, it represents the temporal behavior of solar-type activity, namely, how the starspot cycle becomes more pronounced as the star decelerates and the chromosphere weakens.

When the rotation of a young star slows, the chromospheric and the coronal activity seems to decline synchronously. The solar-like activity of the most F- and early G-type main-sequence stars evolve by this path. However, the activity of lower mass stars, from G5 to K7, after a certain point evolves differently: the chromospheric activity diminishes to the solar level, while coronae stay stronger than that of the Sun. Two possible paths of the evolution of activity can be associated with the different depth of the convective zone of these stars (Katsova et al., 2013). Physically, this means that the relative contribution of local (small-scale) and large-scale magnetic fields to activity differs for F-, G- and K-type stars. The solar-like dynamo tells us that the large-scale magnetic fields are generated in the bottom of the convection zone, in the tachocline, while the small-scale fields are originated in subphotospheric layers. Therefore the location of the lower boundary of the convection zone is important parameter.

### 2.2. On the activity-rotation relationship and different regimes of stellar activity

The first evidence for the dynamo-induced nature of stellar coronal activity was obtained by Pallavicini et al. (1981), who found that the X-ray luminosity in accordance with Einstein observations scaled with the projected rotational velocity as $L_X \propto (v \sin i)^{1.9\pm0.5}$ (or $L_X \propto P_{\text{rot}}^{-2}$, where $P_{\text{rot}}$ is the rotation period of a star), and no dependence on bolometric luminosity. This relationship between rotation and activity was found to break down when X-ray luminosity reaches a
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Figure 1: The "chromosphere – corona" diagram for F-, G- and K-type main-sequence stars. Notes: the grey ellipse marks conditionally the area where the stars with saturated activity regime are located; green triangles (28 stars) and magenta circled crosses (48 stars) are stars with detected lithium abundances (Montes et al., 2001; López-Santiago et al., 2010; Maldonado et al., 2010; Mishenina et al., 2012). Red circles (11 stars) and blue asterisks (8 stars) note the HK-Project stars with Excellent and Good starspot cycles (Baliunas et al., 1995); black dots (158 objects) are the stars discovered during Exoplanet Search Programs. The green straight line corresponds to the ratio for the gyrochronology of Mamajek and Hillenbrandt (2008). The Sun at the maximum and minimum of the sunspot cycle is marked by an orange solar symbol.

saturation level of $L_X \sim 10^{-3}L_{bol}$ (Micela et al., 1985) independent on spectral type (increasing with decreasing bolometric luminosity). This saturation level is reached at a rotation period that increases toward later spectral types (Pizzolato et al., 2003). It was unclear what a cause of this saturation is: a saturation of the dynamo itself, or a saturation of the filling factor of active regions on the stellar surface (Vilhu, 1984). But once saturation occurs, the X-ray emission becomes a function of only the bolometric luminosity (Pizzolato et al., 2003), or effectively the mass, color, or radius of the main-sequence star.

Rather than the rotation period, studies of the rotation-activity relationship frequently use the Rossby number $Ro = P_{rot}/\tau_{conv}$, which is the ratio of the stellar rotation period $P_{rot}$ to the convective turnover time $\tau_{conv}$, in that part of the convection zone where dynamo activity is situated. This dimensionless value is an important parameter of astrophysical dynamo for characteristics of convective motions in a stellar convection zone. It depends on both axial rotation rate and spectral type, and is a measure of the importance of Coriolis forces in introducing helicity into convective motions (Noyes et al., 1984).

The largest sample to date (more than 800 solar- and late-type stars, including both field stars and stars in nearby open clusters of ages 40 – 700 Myr) with well-measured X-ray luminosities and photometric rotation periods has been adopted from the literature by Wright et al. (2011). An analysis of this consolidated catalogue showed that the relation between rotation (in the form of the Rossby number, $Ro = P_{rot}/\tau$) and stellar activity (in the form of the X-ray to bolometric luminosity ratio, $R_X = L_X/L_{bol}$) can be divided into the unsaturated, saturated, and even supersaturated regimes for the fastest rotators of the coronal X-ray emission (Wright et al., 2011; Reiners et al., 2014).

Stellar activity can be in the saturated regime with the coronal index $log R_X \approx -3$, a state of young stars in which activity is independent of rotation. High-level irregular, chaotic activity of these stars evolves eventually into another regime, a second mode, solar-type activity, which strongly depends on the rotation period. In this regime, coronal emission can be as low as the current quiet Sun ($log R_X = -7.1$ in the minimum of the solar cycle; e.g., Peres et al. 2000). As the name implies, in particular, formation of a more or less regular cycle is possible for such typical active phenomena as starspots, active regions, flares and coronal mass ejections (CMEs).
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Figure 2: X-ray to bolometric luminosity ratio versus rotation period, for G- and K-type stars extracted from the catalog by Wright et al. (2011). G- and K-type stars are marked by red and blue symbols, respectively: filled symbols relate to the saturated activity regime, empty symbols denote the unsaturated mode of activity. The location of the Sun is marked by its symbol.

Although there are some stars in the saturated regime – e.g., AB Dor, LQ Hya, with photometric variability where multi-periodicity were revealed. Perhaps, saturated stars just have spot cycles, but not plage cycles, they surfaces too full with active regions, and hence there is no activity cycle in either the chromosphere or the corona. Note that we are talking about regular steady cycles in all tracers of activity. But sometimes it is difficult to separate "true" cycles from stochastic variations, because the resolved time-scales of stellar activity are insufficient to decide reliably that a cyclic variation for a particular star is similar to the well-known 11-yr sunspot cycles. We carried out the wavelet analysis of the longest available stellar activity record – photometric monitoring of a young star V833 Tau for the 120 yr; it reveals that variations obeys the continuous spectrum of fluctuations without any significantly pronounced peaks. We find that the observed variations of V833 Tau with time-scales of 2 – 50 yr should be comparable with the known quasi-periodic solar mid-term variations, whereas the true cycle of V833 Tau, if it exists, should be of about a century or even longer (Stepanov et al., 2020).

The evolution of activity in both regimes are traced separately for G- and K-type stars in Fig.2, where the coronal indices are plotted against rotation periods, based on data extracted from the catalog by Wright et al. (2011).

As seen in Fig.2, the period span of the saturated activity epoch for G-type stars is shorter than that of K-type ones, and the transition from saturation to unsaturated regime occurs at different rotation periods for G- and K-type stars. In order to clarify in more detail when the saturated regime changes to the unsaturated mode of solar-type activity, we carried out more refined analysis (Nizamov et al., 2017) of the same dataset as in Reiners et al. (2014). We considered G-, K- and M-type dwarfs separately and showed that the transition from the saturated activity mode to the solar-like one takes place at the rotation periods of 1.1, 3.3 and 7.2 days for G2-, K4- and M3-type stars, respectively.

This result allows us to estimate the time interval, when the sunspot cycle could appear in the Sun. It appears, that for solar-type stars, the saturated activity epoch ends at the ages of $0.2-0.6 \text{ Gyr}$. After this age, the solar-type activity regime begins to be established, and conditions for formation of a starspot cycle are created. Thus, the sunspot cycle could initiate itself on the Sun at periods of 1 – 3 days, and that the epoch of the solar-type activity covers a wide interval of the rotation periods and can last from the ages of hundred millions to a few billions of years.

Recently Curtis et al. (2019) found that stars cooler than G2 start to slow their spindown, with the slowing increasing with lower mass, i.e. K-type dwarfs appear to spin down more slowly than F- and G-type dwarfs. This means that gyrochronology only works for solar-type ($\sim$G2) stars and more massive stars. These changes in activity regimes may be due to different dynamo configurations.

2.3. Properties of Activity of the Young Sun

According to modern ideas on the internal structure and evolution of solar-mass stars, there are differences between early stage of evolution and epoch when a star is located on the main sequence. So, parameters of a star on a way toward the main sequence in pre-main sequence (pms) stages change much faster than those during its further life on the main se-
sequence. During the first pms-stage lasting a few millions of years, a fully convective star turns into a normal, almost steady star with the radiative core and convective envelope. Then after about 50 Myr the main-sequence stage arrives, which continues for about 9 Gyr (Baturin et al., 2017). Now our Sun is a main-sequence G2 V star of intermediate age, 4.6 Gyr old, with the effective temperature of $\sim 5775$ K. According to the standard model (e.g., Bahcall et al. 2001), the current solar luminosity has increased by 30% as compared to that on the pms, and its radius and the depth of the convection zone are 10% larger.

The lifetime of the Sun on the main sequence can be divided in a few epochs: the early Sun when the Solar Planetary System just was forming, when the solar rotation rate was 10 – 20 times faster than nowadays, the era of the young Sun when a cycle was established (the rotation rate was 2 – 5 times faster), and the contemporary epoch of the slow-rotating Sun.

Activity in solar-like stars over this wide range of ages has been investigated in "The Sun-in-Time" program, started almost 30 years ago (Güdel et al., 1997; Ribas et al., 2005). This multi-wavelength project aimed to trace changes in the coronal and chromospheric emission over the lifetime of the Sun on the main sequence. It was useful, in particular, for studying effects of high energy radiation on exoplanets around the stars.

Beside the results of the long-term monitoring of the stellar chromospheres begun by the Mt Wilson HK-Project mentioned above, the main data sources for activity diagnostics in the chromospheres and transition regions were several space missions, in particular, International Ultraviolet Explorer (IUE) satellite, Extreme Ultraviolet Explorer (EUVE) and Hubble Space Telescope (HST). Extensive research of stellar coronae was carried out using the ROSAT, Einstein, ASCA, Chandra and XMM-Newton (see Guinan and Engle (2009) for details). Five solar analogs (G0 V-G5 V stars) of different ages were selected for their program, and the collected data allowed them to estimate the physical parameters of activity of the young Sun. The following stars were selected: EK Dra (G1.5 V, with age of 130 Myr) with the rotation period $P_{\text{rot}} = 2.8$ d, $\pi^1$ UMa (G0.5 V, 300 Myr) with $P_{\text{rot}} = 5$ d, $\kappa^1$ Cet (G5 V, 750 Myr) with $P_{\text{rot}} = 9.3$ d, $\beta$ Com (G0 V, 1.6 Gyr) with $P_{\text{rot}} = 12$ d, and $\beta$ Hya (G0 V, 6.7 Gyr) (Güdel et al., 1997; Ribas et al., 2005).

Results of the "The Sun in Time" program allowed us to assess the physical conditions in coronae of the youngest G-type stars, which are very powerful: the X-ray luminosity, $L_X$, is up to a few times of $10^{38}$ erg/s, coronal temperatures reaches $10^7$ K, electron densities at the base of the corona are $3 – 5 \times 10^9$ cm$^{-3}$, and the emission measure is $10 – 30$ times higher than that in active regions on the contemporary Sun. For example, the coronal indices for EK Dra and $\kappa^1$ Cet are log $R_X = -3$ and $-4.4$ respectively, indicating that the X-ray luminosity of the young Sun exceeded that from the present-day active Sun by $3 – 4$ orders of the magnitude. In addition, with age, the coronal emission became cooler (Ribas et al., 2010).

In order to understand the impact of the young Sun on the origin of the biosphere and the geological history of the Earth, it is important to evaluate the intensity of the EUV radiation, quasi-steady outflows of the plasma and fluxes of high energy accelerated particles affecting the radiation environment in that era. The stellar UV excess is roughly proportional to thechromospheric index $R_{\text{HK}}$ or to stellar age, at least for stars younger than 1 Gyr (Findtsemen et al., 2011). We have selected here 15 fast-rotating solar-like G-type stars of approximately that age for estimation their EUV-fluxes. We have used data obtained with GALEX (Galaxy Evolution Explorer) in two wide spectral ranges: Near-UV 1750 – 2750 Å and Far-UV 1350 – 1750 Å (Bianchi et al., 2011). The EUV-range is more sensitive to activity level and is spared from the problems with the flux saturation. For these 15 stars, we collected the GALEX FUV-fluxes from Bianchi et al. (2011), and then recomputed these fluxes at the distance 1 a.u. in erg/(cm$^2$ s), then calculated the star-to-Sun flux ratio (Table 1).

We obtained that the mean FUV-flux is $13.9\pm3.5$ erg/(cm$^2$ s) at the distance of 1 a.u. for 15 young main-sequence G-type stars; this value exceeds the FUV-flux of the contemporary Sun by the factor of almost 7. For a proxy of the Young Sun, comparison of $\kappa^1$ Cet spectra, given by Ribas et al. (2010), with the solar one showed that their contrast in the UV continuum (1000 – 1700 Å) is equal to 2. This means that the young Sun irradiated the terrestrial surface in the UV range several times more intense in the era of formation of the biosphere, when life arose on the Earth, than today.

### 2.4. On magnetic fields, mass losses, and CMEs of Young Suns

Magnetic field generation in cool stars is caused by a dynamo process which is primarily an interaction between rotation (and its shear) and convection. Magnetic activity becomes stronger with faster stellar rotation. As mentioned above, magnetic fields decrease with stellar age, as we pass from fast rotators to slowly rotating stars.

In order to find out the energetics of quasi- and non-steady processes on the young Sun, which occurred when the regular sunspot cycle was established, we need magnetic field observations. These measurements were carried out in the frameworks of the spectropolarimetric Bocool project magnetic survey of 170 solar-type stars by Marsden et al. (2014). The detected surface magnetic fields were found on 67 objects. It was established, that in general, the mean value of the strength of the magnetic field $|B_l|$ increases with rotation velocity and decreases with age. For all G-type dwarf star samples, the mean value of the strength of the magnetic field $|B_l|$ was found 3.2 Gauss. In particular, the modulus of the longitudinal magnetic field for young solar analog $\kappa^1$ Cet is equal to 7.7 Gauss. It is important to note that these ZDI field measurements detect only the residual large-scale fields after dominant small-scale cancellation effects (Kochukhov et al., 2020).

For evaluation of the magnetic field of the Young Sun, we selected samples of G-type dwarf stars with values $|B_l|$, page 6 of 12
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Table 1

The GALEX FUV-fluxes for 15 solar-like G-type stars. The table contains the names of the stars (1), spectral types (2) and parallaxes, in milliarcseconds (3), the measured GALEX FUV-fluxes, in microJansky (4) from Bianchi et al. (2011), FUV-fluxes, recalculated to the distance 1 a.u., in erg/(cm² s), (5), and the star-to-the Sun flux ratio (6).

| N  | Star Name   | Spectral type | Parallax, milliarcseconds | Flux, microJansky | Flux at 1au, erg/(cm² s) | Flux ratio Star/Sun |
|----|-------------|---------------|---------------------------|-------------------|--------------------------|---------------------|
| 1  | HD 224540   | G0            | 22.40                     | 15.77             | 6.79                     | 3.40                |
| 2  | HD 138159   | G3 V          | 14.83                     | 16.67             | 16.39                    | 8.20                |
| 3  | HD 19423    | G2 V          | 19.51                     | 20.81             | 11.82                    | 5.91                |
| 4  | HD 212619   | G3 V          | 14.86                     | 17.08             | 16.72                    | 8.36                |
| 5  | HD 131179   | G5/6 V        | 25.26                     | 33.09             | 11.21                    | 5.61                |
| 6  | HD 218614   | G5 V          | 18.66                     | 27.50             | 17.06                    | 8.53                |
| 7  | HD 221343   | G2 V          | 19.76                     | 29.22             | 16.18                    | 8.09                |
| 8  | HD 119824   | G0            | 21.34                     | 20.69             | 9.82                     | 4.91                |
| 9  | HD 12264    | G5 V          | 24.46                     | 44.65             | 16.13                    | 8.07                |
| 10 | HD 214867   | G3 V          | 16.77                     | 17.46             | 13.42                    | 6.71                |
| 11 | HD 109360   | G5            | 15.33                     | 10.21             | 9.38                     | 4.69                |
| 12 | HD 211847   | G5 V          | 20.49                     | 31.78             | 16.36                    | 8.18                |
| 13 | CD-33 15016 | G2            | 9.80                      | 64.86             | 14.61                    | 7.31                |
| 14 | HD 222628   | G2 V          | 10.60                     | 63.90             | 12.31                    | 6.16                |
| 15 | HD 30386    | G3 V          | 10.94                     | 10.79             | 19.48                    | 9.74                |

exceeding 3σ, excluding the youngest, fast rotating stars. For the dozens of G-type stars with the rotation period $P_{rot} = 7$ days, we obtained this averaged value as $|B_1| = 4.72 \pm 0.53$ Gauss. We compared this value with the global magnetic field of the contemporary Sun as a star near the maximum of the sunspot cycle. The averaged over the Carrington rotation the magnetic fields of the Sun as a stars at high activity level (for example, in 1991), is $|B_1| = 0.5$ Gauss (Kotov et al., 1999). From here we can conclude that the average magnetic field strength of the young Sun, when the sunspot regular cycle arose, was at least an order of magnitude higher than that for the maximal Sun in the modern era (Katsova and Livshits, 2014). Note also that the local magnetic flux in plage of young low-mass stars can reach 3 – 5 kG, and active regions can cover up to 20 – 30 % of the stellar surface (Saar, 2001; Reiners and Basri, 2008).

The rotational evolution of low-mass stars is governed by an angular momentum loss caused by the interaction of the star’s magnetic field with its ionized wind. It is potentially possible to evaluate the mass loss of a star of a given age, in the case when its rotation rate is known. This opens a way of finding out the mass loss rate by the young Sun. This only works if the angular momentum loss theory is correct.

The plasma in the wind escapes its host star at the distance where the wind reaches the Alfven speed $v_A = B/(4\pi\rho)^{1/2}$, where $B$ is the local magnetic field strength, and $\rho$ is the local mass density. $\rho = nm_p$ is the mass density ($n$ is the number density and $m_p$ is the proton mass). Beyond this surface, the wind velocity exceeds the Alfven speed, and the wind is no longer in contact with the star via magnetic fields.

As the first step, the mass loss can be estimated from the expression by Weber and Davis (1967) relating mass and angular momentum loss. The total angular momentum loss rate is $dJ/dt = -2/3\Omega M R_A^2$, where $dJ/dt$ is the angular momentum loss rate, $\Omega$ is the angular velocity, $M$ is the mass loss rate, $R_A$ is the average distance from the center of the star to a given point on the Alfven surface, and where a constant radial magnetic field is assumed at the surface of the star. This expression is good for a case of a spherically-symmetric wind, a magnetic field that is close to a uniformly distributed one across the Alfven surface, and constant moment of inertia for the star (i.e., one assumes the time scale for angular momentum loss in this expression is short relative to the evolution of the star’s internal structure). This description breaks down for more complex magnetic topologies. Note also that this is appropriate for rotating main-sequence stars when their mass and radius do not vary with time.

The mass loss rate can be also evaluated from the following equation for the total torque of the star $M = \tau_u/\Omega R_A^2$, where $\tau_u$ is the stellar torque, $\Omega = 2\pi/P_{rot}$ is the angular velocity, and $R_A$ is the radius of the Alfven surface.

For the early Sun at ages in the range 300 – 750 Myr, we adopt values for the rotation period of 5 days, the plasma density, where the outflow starts, is 10 – 20 times solar, and a large-scale magnetic field strength $B = 5$ Gauss. In this case the quasi-steady mass loss rate is about $10^{-12} M_\odot$/year. This value can be increased by a factor of 2, if we take into account also the dynamic processes like coronal mass ejections which happened apparently more often at that era. Our estimates agree with those obtained by Cohen and Drake (2014).
plasma outflows from the corona. 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. Even if the soft X-ray radiation of the G-type star reaches the saturation level, i.e., $3 - 4$ orders of magnitude larger than 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 contemporary Sun. However, the high-speed wind of the young Sun must be amplified because the plasma density at the base coronal hole (or the polar region) increases, while the outflow is formed at higher coronal levels. It means that the contribution of the low-speed and high-speed streams to the quasi-steady mass loss can be similar.

It is clear that non-steady processes were more frequent in the young Sun’s corona. Observations show that a large solar flare with the energy of about $10^{31}$ erg is accompanied by CME ejected mass of about $10^{16}$ g (Drake et al., 2013). We can estimate the CME mass loss by $k^1$ Cet if we turn to results of the Kepler mission, which discovered superflares on solar-mass stars (Shibayama et al., 2013). This study contains statistics on the occurrence frequency of the large flares. It shows that for $k^1$ Cet, the occurrence frequency of a flare with the energy of about $10^{34}$ erg is $2$ orders of magnitude higher than that for most active solar-type stars (Fig. 9 in Shibayama et al., 2013). An extrapolation of this value to weaker phenomena with an energy of $10^{31}$ erg under the same law as in Shibayama et al. gives us the occurrence frequency of such events around $(2 - 3) \times 10^{-26}$ erg$^{-1}$ star$^{-1}$ year$^{-1}$. This leads to the value of $2 \times 10^7$ events per year and corresponds to the CME mass loss of about $10^{-12} M_\odot$ year$^{-1}$. Although this value is only $10\%$ of the possible rate of quasi-steady outflow of the young Sun, the contribution of CMEs could be significantly higher than today.

Recently do Nascimento et al. (2016) taking into account data on the large-scale magnetic field have been obtained the plasma outflow rate for $k^1$ Cet close to $10^{-12} M_\odot$ year$^{-1}$. The similar value for this star was obtained by modelling of 3D-structure of stellar winds carried out by Ő Fionnagáin et al. (2019). Improved detailed modelling of the CMEs emitted by $k^1$ Cet was made by Kay et al. (2019).

Thus, the total mass loss of the young Sun was quite high, up to a factor of few times by $10^{-12} M_\odot$ year$^{-1}$. If this rate is maintained for about a billion years, it would 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.

2.5. Remarks on stellar superflares

The detection of extremely powerful non-steady phenomena, superflares, on G-type stars with the Kepler mission raises an alarming problem: can superflares happen on the present-day Sun, because their consequences can be catastrophic for our contemporary high-tech civilization. From the other hand, it gives a possibility to study flare activity of the Sun at different ages, i.e. at different rotation periods.

The energy and occurrence frequency of the largest flares (superflares) on the young Sun can be evaluated from data provided by the Kepler mission that had monitored several hundred thousand stars during 10 years (2009 to 2018). In the short-cadence mode with the 1-min temporal resolution 187 flares with the total energy from $2 \times 10^{32}$ erg to $8 \times 10^{35}$ erg were detected from 23 G-type stars. One of the general conclusions of this mission was that only $0.2\%$ to $0.3\%$ of solar-type stars show superflares, while $> 40\%$ of the original solar-type superflare stars in previous studies are now classified as subgiants. The statistics of Kepler’s superflares offered the following estimates for the mean occurrence frequency of events: flares with the total energy $10^{33}$ erg can occur once per $70 - 100$ years, flares with the energy of $10^{34}$ erg occur once in about $500 - 800$ years, and superflares with the energy of $10^{35}$ erg can happen once in about $4000 - 5000$ years (Maehara et al., 2015).

It is worthwhile to emphasize that stellar superflares with the total energies larger than $10^{35} - 10^{36}$ erg apparently occur on the youngest fast-rotating stars the saturated regime of activity, on subgiants and giants, as well as on components of close binary systems (Katsova and Nizamov, 2018).

An important question remains whether superflares with energies up to $10^{35} - 10^{36}$ erg are possible at all on the Sun at present time. For comparison, the contemporary Sun demonstrates 1144 proton flares accompanied by proton events with $E \geq 10$ MeV during 1975–2003 that corresponds to 41 events per year according to an IZMIRAN database (Belov et al., 2005).

In order to evaluate the upper limit of the energy of flares that are able to occur in a given large active region, we carried out an analysis of observations of the total magnetic field vector, applying the method of the non-linear force-free field (NLFFF) extrapolation. The NLFFF approximation gives information on the magnetic field structure in the corona of active regions (AR). It is assumed that the magnetic field above the photosphere can be regarded as a force-free field. Each AR has its specific magnetic configuration characterized by the energy of the magnetic field. The development of non-steady processes in ARs is governed by the difference of this magnetic energy from the energy of the potential field, but not by the total magnetic energy itself. This difference is characterized by the free energy. The amount of the free energy increases with the emergence of a new magnetic flux, and free energy is presumably responsible for flares and CMEs. If one considers only the total energy of non-steady processes, it is possible to shift from the equations describing the structural features to considering the magnetic virial theorem. An analytic expression for the free energy of the solar corona as a whole was suggested earlier by Livshits et al. (2015) which let us assess an absolute upper estimate of the energy of flares that are possible for a given large active region. We found that even the largest active regions on the Sun are not able to produce non-steady processes like flares and CMEs with the total energy greater than $3 \times 10^{32}$ erg.
Consequently, flares stronger than this value cannot occur on the contemporary Sun (Livshits et al., 2015; Katsova and Livshits, 2015). This is approximately equal to the total energy estimated for the Carrington event, $2 \times 10^{32}$ erg.

Considering the star $\kappa^1$ Cet as an analog of the young Sun, one could derive the following parameters of its activity: the X-ray luminosity is $L_X = 10^{29}$ erg/s, occurrence frequency of flares with the total energy $E > 10^{32}$ erg is 5 events per day or 1825 events per year (from EUVE data by Audard et al. 2000), and its surface is more spotted (by a factor of 10 – 20). The average longitudinal magnetic fields of G stars (at an age of 0.6 – 1 Gyr) are 10 – 15 times stronger than the maximum magnetic field of the Sun as a star (as it follows from the results by the Be cool collaboration, see the previous section). Therefore, because the total flare energy that is proportional to $B^2$, the maximal possible flare energy of young G-type stars cannot exceed $5 \times 10^{34}$ erg. It is consistent with the statistics for the Kepler targets among the main-sequence stars with the rotation periods around 10 days. Only flares with these total energies can be considered as solar-type analogs of impulsive events, associated with the energy deposit in and above the chromosphere with its subsequent release, as it happens on the Sun. So, the stronger events require for their explanation, either non-solar analogies for the origin of flares or appropriate changes in the dynamo mechanism (Katsova et al., 2018). From the other hand, taking into account new results by Kochukhov et al. (2020) on real unsigned small-scale strong magnetic fluxes with a big filling factor on a surface of young solar-type stars, it could be possible to obtain also more energy for superflares.

**3. Discussion**

In this study we summarize the key points of the scenario of the evolution of activity:

- the evolution of solar-stellar activity follows the temporal behavior of the angular momentum of a star. A joint consideration of the rotation-age and activity-rotation relationships gives a possibility to explore of basic indicators of activity for solar-type stars of various ages.

- As demonstrated in the empirical trends traced in recent studies of stellar magnetism, after the 100 – 250 Myr, magnetic fields evolve in a close correlation with rotation and determine the pattern of activity over the next billions of years.

- It is now clear that the lifetime of the Sun on the main sequence can be divided in a few epochs: the early Sun when the Solar Planetary System just was forming, when the solar rotation rate was $10 – 20$ times faster than nowadays; the era of the young Sun when a regular cycle was established (the rotation rate was $2 – 5$ times faster), and the contemporary epoch of the slow-rotating Sun. Each of these epochs is characterized by different behavior of the basic tracers of activity.

- The activity of the early Sun is similar to young solar analogues, showing a very high level at the saturated regime.

- It is characterized by large active region area, a dense, active coronae with the maximum level of the coronal activity ($\log L_X / L_{bol} = -3$), superflares, enhanced lithium abundance, and strong plasma outflows. Saturation is also present in large-scale magnetic fields. This epoch is characterized by independence of the main activity tracers on rotation.

- As the rotation of solar-mass main sequence stars is slowed by its magnetized wind, the saturated regime of activity changes to the unsaturated mode, when activity indices decline in tandem with rotation. This solar-type activity with formation of the regular activity cycle, as oscillating dynamo does turn on, occurs when the rotation period of a G-type star (the young Sun) reaches a value of about few days.

**4. Conclusions**

This study briefly summarizes the results of many laborious long-term observational programs conducted by large scientific teams and dedicated to investigations of different aspects of stellar activity. Their results are considered in the context of general ideas, which facilitate an understanding the evolution of solar activity from its arrival on the main sequence through the epoch of the sunspot cycle formation up to the present days. Basic astrophysical laws, derived for the rotation-age and activity-rotation relationships, allowed us to trace how activity of low-mass stars changes with age during their stay on the main sequence. Recent results clarify, complement and expand the general ideas on the evolution of solar and stellar activity. We focus on the activity properties of stars that can act as proxies for the early and the young Sun. Our analysis includes joint consideration of different tracers of activity, rotation and magnetic fields of Sun-like stars of various ages and helps to understand the physics of these phenomena.

We identify rotation periods, when the saturated regime of activity changes to the unsaturated mode, when the solar-type activity is formed: for G- and K-type stars, they are 1.1 and 3.3 days, respectively. This corresponds to an age interval of about 0.2 – 0.6 Gyr, when regular sunspot cycle began to be established on the early Sun.

Properties of the coronal and chromospheric activity of the early and the young Sun are discussed. Our analysis of the EUV-fluxes in the spectral range of 1350 – 1750 Å showed that the far-UV radiation of the early Sun was by a factor of 7 more intense than that of the present-day Sun, and twice higher when the regular sunspot cycle was established.

For the young Sun, we can estimate the possible mass loss rate associated with quasi-steady outflow as $10^{-12} M_{\odot}/yr$. Studies of the largest flares on solar-type stars have also been discussed and we concluded that the most powerful phenomena occur on fast-rotating stars in the saturated activity regime. Our estimate of stellar magnetic fields offers a possibility to estimate the maximum possible flare energy. This value for flares on young main-sequence G-type stars with

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the rotation period $P_{\text{rot}} \approx 8 \times 10^3$ d and ages 600 Myr–1 Gyr was assessed as not to be in excess of $5 \times 10^{34}$ erg. For such events, we conclude that their origin is similar to solar one: when the free energy is accumulated in the chromosphere and then this deposited energy is released in the course of a non-steady process.

As for superflares on the Early Sun with the total energy $10^{35} - 10^{36}$ erg, the mechanism of such phenomena obviously differs from that accepted for contemporary solar flares, and possibly can be associated with the evolution of the large-scale magnetic fields or another dynamo regime. Further study of these problems should help in understanding the origin of extreme events on the Sun in the past, which is important for establishing the physical conditions in the heliosphere from an epoch of formation of the solar planetary system, in general, the early Earth and, in particular, the origin of terrestrial biosphere.

5. Acknowledgements

I am grateful to the SOC of VarSITI Completion General Symposium (held in Sofia, Bulgaria on June 10-14, 2019) for the invitation and possibility to present these results. I am thankful to anonymous reviewers for helpful remarks that help to improve this paper.

I am deeply grateful to Dr. S. Saar for useful discussions and comments.

This work was carried out with the partial support by the Russian Foundation for Basic Research (project numbers 19-02-00191a and 18-52-06002 Az_a). This research has also made use of NASA’s Astrophysics Data System.

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