SUPERFLARES AND CYCLES AS STAGES OF THE EVOLUTION OF STELLAR ACTIVITY

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Current observations allow us to consider changes of the solar-stellar activity in the evolutionary aspect. Development of active processes is determined by physical parameters of a star, when it arrives to the main sequence. At birth, low-mass stars in the open cluster have a large dispersion of rotation, which decreases rapidly due to the fact that rapid rotators are slowed down more effectively. During the first 1 Gyr, the initial dispersion almost disappears. To this epoch, magnetic fields are formed that evolve in a close correlation with rotation and determine the pattern of activity over the next billions of years.
Distinctions between the saturated regime of activity intrinsic to the youngest, fast rotating low-mass stars and stars with the solar-type activity, when a cycle begins to be established, are considered. Changes in the regime of activity are discussed in the context revealing epochs of the cycle formation on stars of different spectral types.
Discovery of the most powerful non-stationary phenomena like superflares on G-type stars during the Kepler mission is a challenge that outlined the new challenges to be addressed. Now it is clear that the largest superflares occur rather on fast rotators, i.e. on stars, whose activity is in the saturated regime and which possess the maximal magnetic activity. Joint analysis of observations of superflares and available data on stellar magnetic fields on solar-type stars gives a chance to estimate the maximal possible energy of stellar flares and to understand their origin.
Keywords: Stars: late-type stars, flares, activity – Sun: flare – Sun: activity

1. INTRODUCTION

The solar corona is a high-temperature layer of the solar atmosphere. The I present here an incomplete and brief review of some problems associated with superflares and an evolution of stellar activity.

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First, we consider here some introductory remarks concerning the evolution of the stellar activity. Many evidences for active phenomena in most of stars with masses $< 1M_{\odot}$ and an effective temperatures $\leq 6000\ K$ are observed in different spectral ranges since 1960th. These stars possess a radiative core and an outer convective zone. The magnetic field is generating there through a dynamo process. It creates a complex of active phenomena of magnetic acivity that can be considered well studied mostly only on the Sun.

Observations of different tracers of stellar activity showed that the main factor determining the activity level is the axial rotation of a star. Study of open clusters of different ages shows that at birth, low-mass stars have a large dispersion of rotation rates, because the process of star formation is not instantaneous. This scatter decreases rapidly due to the fact that rapid rotators are slowed down more effectively. During the first 1 Gyr, the initial dispersion almost disappears, and most of stars rotate with periods, corresponding to their age. This was the basis for estimate the age of a star from its rotation period – a method of the gyrochronology (Mamajek and Hillenbrandt, 2008, Barnes et al., 2016).

From the other side, now it is clear that development of activity is determined by physical parameters of a star, when it arrives to the main sequence. To this epoch, magnetic fields are formed that evolve in a close correlation with rotation and determine the pattern of activity over the next billions of years. Results of such an evolution of activity we can directly feel and watch on the contemporary Sun.

2. ON DIFFERENT MODES OF STELLAR ACTIVITY

Change in a regime of activity of low-mass stars of various spectral types was analized by Nizamov et al. (2017). We studied the dependence of the coronal activity index on the stellar rotation rate. This question was considered earlier for 824 late-type stars on the basis of a consolidated catalogue of the soft X-ray fluxes registered with *Einstein, ROSAT, XMM-Newton* (Wright et al. 2011, Reiners et al. 2014). These data indicated the existence of the two modes in in the dependence of the coronal activity index, $R_X = \log L_X/L_{bol}$ on the rotation period (or the Rossby number). So, stellar activity can be in the saturated regime with the coronal index $R_X = -3$, it is characteristic of young stars and is practically not related to their rotation. High-level irregular, chaotic activity of these stars evolves gradually into another regime, the second mode, which strongly depends on the rotation period. It corresponds to the solar-type activity and implies, in particular, formation of a more or less regular cycle, along with such typical phenomena as spots, active regions, flares and CMEs. Our more refined analysis carried out separately for G, K and M dwarfs showed that the transition from one mode to another takes place at the rotation periods of 1.1, 3.3 and 7.2 days for the stars of spectral types G2, K4 and M3 respectively. This means 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 for a star of the solar mass.

In the light of the discovery of superflares on G and K stars with the Kepler mission there arises a question of how these objects differ from other active late-type stars. We analyse the location of superflare stars relative to the stars observed by *Kepler* on the "amplitude of rotational brightness modulation (ARM) — rotation period" diagram. The value of ARM reflects the relative spots area on a star and characterises the activity level in the whole atmosphere. It is shown that G and K superflare stars are basically fast rotating young objects, but some of them belong to the stars with the solar type of activity.

3. THE STRONGEST FLARES ON THE SUN AND OTHER LOW-MASS STARS

The Kepler epoch: The first results of the Kepler mission caused a sensation: they reported about registration of superflares on solar-type stars. It was launched on March 7, 2009 and deactivated on November 15, 2018) registered from April 2009 to May 2013 (Q0 – Q17). In the wide range of the optical continuum 4300—8900 A it was discovered 1547 solar-type stars 5300 $K < T_{eff} < 6300$ K and $4.0 < \log g < 4.8$. Only 0.2 to 0.3% of solar-type stars show superflares. In short-cadence mode with the 1-min resolution were registered 187 flares with the total energy from 2×10^{32} erg to 8×10^{35} erg in the only 23 such stars. Recent statistics of Kepler's superflares gives the following estimates for the mean flare occurrence frequency on the solar-like stars for events with the total energy 10^{33} erg is one event per 70–100 years, 10^{34} erg — occurs once in about 500–800 years, and 10^{35} erg is once in about 4000–5000 years (Maehara et al 2015).

The average rate of appearance of an X100 class flare on a G star with the rotation period of $P_{rot} = 25$ day like the contemporary Sun is one event in 500–600 years.

We have been analysed also where the Kepler mission registered the largest superflares (Katsova, Nizamov, 2018) and showed that the only 7 of 46 single cool giants or subgiants, whose variability is associated with spots, listed by Balona (2015), demonstrate superflares with $E > 10^{36}$ erg. Thus, such powerful phenomena occur mainly on subgiants and giants.

Recent analysis of the Kepler data by Notsu et al (2019) showed that more than half (43 stars) are confirmed to be "single" stars, among 64 superflare stars. They "investigated the statistical properties of Kepler solar-type superflare stars

	KIC / HD	T_{eff}, K	$\log g$	$R, (R_\odot)$	P_{rot}, day	N flare	$\log E$, erg
1	2852961	4722	2.919	5.499	8.8	5	38.18
2	4273689	5173	3.471	2.742	29.943	8	36.38
3	5733906	5430	3.676	2.365	0.719	7	36.11
4	6437385	5727	3.707	2.061	13.672	18	36.78
5	226464	6028	4.044	1.535	3.101	15	36.44
6	9833666	5624	3.712	2.702	10.341	9	36.27
7	10976930	6197	3.657	3.01	2.054	2	36.32

by incorporating Gaia-DR2 stellar radius estimates. As a result, the maximum superflare energy continuously decreases as the rotation period P_{rot} increases. Superflares with energies $< 5 \times 10^{34}$ erg occur on old, slowly-rotating Sun-like stars ($P_{rot} \sim 25$ days) approximately once every 2000—3000 years, while young rapidly-rotating stars with $P_{rot} \sim$ a few days have superflares up to 10^{36} erg. The maximum starspot area does not depend on the rotation period when the star is young, but as the rotation slows down, it starts to steeply decrease at $P_{rot} > 12$ days for Sun-like stars. These two decreasing trends are consistent since the magnetic energy stored around starspots explains the flare energy, but other factors like spot magnetic structure should also be considered."

Many solar-type stars show extraordinary high magnetic activity, which cannot be expected from the solar observations, such as spot activity and superflares. The large starspots are considered to be a key to understand the superflare events as well as underlying stellar dynamo.

Namekata et al. (2019) investigated lifetimes, emergence and decay rates of large star spots on solar-type stars estimated by *Kepler* data by comparing them with well-known sunspot properties. As a result, they found that lifetimes of star spots are ranging from 10 to 350 days when spot areas are 0.1–2.3 percent of the solar hemisphere.

Nevertheless, the large star spots ($\sim$ 10 000 MSH) potential to produce superflares ($\sim 10^{34}$ erg, Shibata et al. 2013) are found to survive for up to $\sim$ 1 year. This implies that the surrounding exoplanets can be exposed to danger of superflares for such a long time. Moreover, according to frequency distributions of superflares, superflares of 10^{34} erg can occur about once a year on the star spots with area $\sim$ 10 000 MSH (Maehara et al. 2017). This may indicate that superflares can occur with a high probability once such large spots emerge on the stellar surfaces.

Thus, further analysis revealed that the largest superflares occur rather on fast rotators, i.e. on stars, whose activity is in the saturated regime of activity and which possess the maximal magnetic activity. Joint analysis of observations of superflares and available data on stellar magnetic fields on solar-type stars gives a chance to estimate the maximal possible energy of stellar flares and to advance in understanding their origin. It will be discussed below.

The Sun: An important question remains whether superflares with energies up to $10^{35} - 10^{36}$ erg are possible on the Sun at present. If not, what is the physical difference between the Sun and the superflaring Sun-like stars? This question is beyond purely academic interest because a solar superflare would be hazardous for modern technology.

On one hand, the energy of the solar magnetic field is insufficient to produce a superflare. On the other hand, cosmogenic isotope studies have identified historical events that were 30-50 times stronger (in the sense of the fluxes of solar energetic particles) than the most energetic solar flares observed instrumentally [see for instance, Usoskin et al. 2013 A&A 552, L3].

Up to now the only a few extreme energetic flares on the Sun are known **in the contemporary epoch** of instrumental observations: events in 1-2. September 1859 Carrington flare (∼X45) (160 years ago!), February 1956, August 1972, March 1989, June 1991, October-November 2003 (4.November 2003 – X28), 6.September 2017 – X9.3 etc.

Even fewer events are known **in the past** as Solar Extreme Events from cosmogenic proxies (radiocarbon ^{14}C in dendrochronology and ^{10}Be in polar ice cores). Because the half-life of ^{14}C is only 5730 yrs, this dating method is used only for dating things that lived within the last 50 000 yrs. So, the strongest events over the Holocene (the current interglacial period started about 11 000 yr ago) occured in $\sim$ 640 BC—660 BC (O'Hare et al. 2019; Hayakawa et al. 2019), 774/775 AD (40×the strongest Solar Energitic Particle event of the instrumental era 23.February 1956), and in 993/994 AD (0.6 weaker than the previous event). Miyake et al. (2019) observed a ∼50% increase in ^{10}Be concentration around hemispheres support a solar origin of the 994-event. Note that cosmogenic proxies have a low time resolution (annual at best).

Thanks to modern high-quality data on the total vector of the magnetic field in active regions, the large-scale magnetic field including the dipole field of the Sun as a star it becomes possible to calculate the free energy of the magnetic field in active regions that can be realised in a flare. These estimates showed that even the lagest active regions on the Sun are able to produce non-stationary processes (flares and coronal mass ejections) with the total energy not greater than 3×10^{32} erg. This is an upper limit for a given active region follows from the magnetic virial theoreme (Livshits et al. 2015, Katsova and Livshits, 2015). Thus, flares stronger than this value, 3×10^{32} erg, can not occur on the contemporary Sun. (Details will be discussed in the next section)

The Great Stellar Flares Observed prior the Kepler Epoch: Except our Sun, prior the Kepler mission, the strongest and best-studied non-stationary events among the low-mass stars were registered on young T Tau stars (for example, four largest optical flares on V410 Tau (K3 V) in November 2001 with energies up to 3×10^{37} erg (Fernandez et al. 2004) and on many red dwarf stars (Gershberg 2005).

Several samples of very strong optical flares on some red dwarf stars are given below:

- a stellar analog of the typical large X-class flare on the Sun occurred on Prox Cen (dM5.5e) August 12, 2001 (Güedel et al. 2002);
- a great flare with $\Delta U > 4.5^m$, duration > 4 hours and the energy $E > 10^{34}$ erg was registered 12.04.1985 on the star AD Leo (dM4.5e) by Hawley and Pettersen (1991);
- a megaflare with $\Delta U = 7.2^m$, $E_u = 7.8 \times 10^{33}$ ergs and $L_{u,max} = 4.6 \times 10^{31}$ erg/s on EV Lac (dM3.5e) on 01.11.1991 was observed by Pettersen (2016);
- a giant flare on CN Leo (dM 6e) in May 19th, 2006 was registered with *XMM-Newton* both in X-rays, Ultraviolet-Visual Echelle Spectrograph (UVES) and in optics onboard and ground-based; $\Delta U > 7^m$ with 1s-resolution. Spectral features of line profiles give evidences for an explosion of the plasma in the optical flare source. An analysis of this flare showed that impulsive stellar flares whose nature differ from commonly accepted model based on the gas-dynamical response can exist (Fuhrmeister et al. 2008, Schmitt et al. 2008).

In general, when the total energy of a stellar flare exceeds $3 - 5 \times 10^{34}$ ergs, similar to this case of CN Leo flare, the nature of such an event can differ from the solar–like non-stationary processes.

There are also very powerful long-duration stellar flares (similar to solar LDE), however they did not registered in optics, but only with space missions: *EUV Explorer* (AU Mic, M2.5e V on 1992, 15-17 July (Katsova et al. 1999) and in X-rays with *BeppoSAX* (chromospherically active binary UX Ari, G5 V+K0 IV (Livshits and Livshits 2002; Livshits et al. 2003).

4. SOME COMMENTS ON THE PHYSICS OF FLARES

As it known, both solar and stellar flares are associated with an evolution of the magnetic fields. A flare is breakdown of stability of MHD-configuration, a sudden energy release, electron acceleration, etc. The scenario of impulsive flares, which is a gas-dynamical response of the chromosphere to the impulsive heating by accelerated particles, is well-studied: after the primary energy release the explosive evaporation starts and leads to the upward motion of the hot gas and formation of the system of loops, filled up gradually with the hot plasmas. 40-year investigations of the explosive evaporation showed that the downward moving low-temperature condensation is the basic source of the flare optical continuum emission of the hydrogen plasma. The energy of the accelerated electron beam, injected into the chromosphere, can not exceed 3×10^{11} erg/(cm^{2}c). This value is limited due to the appearance of the return electric current and is the low limit of the energy of particles accelerated in the pulse and injected gradually from the coronal part of loops into the chromosphere over all flare area (Livshits et al., 1981, Fisher et al., 1985, Katsova et al., 1997).

Note that the optical continuum spectra in the impulsive phase of white-light flares on the Sun and some red dwarf stars exhibit a color temperature of a $T \sim 10^4$ K blackbody. As an example, one can mention observations of a flare on YZ CMi, on 13.01.2012, during which the temperature of the black-body continuum radiation in the impulsive phase changes from 6000 to 10 000 K in the wavelength range 4170–6000 A (Kowalski et al., 2018).

The area of a white-light solar flare is 3×10^{16} cm^2 (solar flares in 1972, June 15, 1991). It is confirmed by current data about the area of the brightest footpoints in the G-band of the WL flare continuum (Krucker et al. 2011). One can estimate the flare area for a stellar flare from the expression $E_{flare} = \sigma T^4 \times S \times \Delta t$. So, the flare with the total energy $E = 10^{34}$ erg and $\Delta t = 30$ min covers the area $S = 10^{19}$ cm^2 that is slightly higher than the maximal area of H_α–ribbon area of the greatest solar flares.

On time scales of some kinds of the soft X-ray solar flares

(after GOES 1-8 A data where $X10 = 1$ erg/(cm^{2}c) near the Earth or 3×10^{31} erg):

- many of impulsive flares are more often weak and last up to 10 min, M5;
- fast, strong flares are compact flares when coronal loops are formed but immediately cool down; their duration is up to 30 min (X2);
- strong two-ribbon flares last 1-2 hours (up to X2);

- long-duration events, LDE, including bright coronal mass ejection and system of giant post-eruptive archs last around 2 – 12 hours, up to 28 hours).

Evaluation of the accelerated electron fluxes for powerful flares

The optical observations of superflares with $E = 10^{34}$ erg give information about the total number of electrons with $E > 20$ keV: $N \approx 10^{38}$ electron/s. This injection is about of 100 times more than in X1 flares on the Sun and this process lasts 30 min. It requires exceptionally effective acceleration of particles (Katsova, Livshits 2015).

On a model of the optical continuum source of superflares

The model of the optical continuum source for a superflare with the total energy of 10^{34} erg is discussed in details in section 3 of the paper by Katsova, Livshits (2015) and based on an analysis of current observations of the strongest solar flares like the Bastille Day flare on 14.07.2000. The first result is the following: the continuum emission arises in loops with a footpoint area comparable with the area of H_α-ribbons of large solar flares. There are several sources of the optical continuum emission. The emission of one of sources is due to gas-dynamical response to the particle flux, which fills up the coronal loop. The optical emission sources of ribbons are low-temperature chromospheric condensations in footpoints of flare coronal loops. In addition to this blue continuum and line emission, the optical continuum of the photospheric layers of the active region arises in low-lying loops near large spots where particles are accelerated (source, associated with a region of the main particle acceleration). There are a few sources of small additional heating of the upper photosphere of G-type stars similar to those in red dwarfs. One of them can be associated with penetration of high-energetic particles from the acceleration site to the photosphere. Each of acceleration episodes provides the red continuum, and the radiation of the condensation arises within a few seconds. As a result, the flare optical continuum extends from the IR- to UV-ranges.

The total energy of the optical radiation of a superflare is the sum of the energies of elementary events, and each of them is characterized by the optical radiation in a broad spectral range. The radiation during the post-eruptive phase also contributes to the total flare energy of the superflare.

Another model of formation of the optical continuum for a superflare on an young G star is proposed recently by Nizamov (2019) where the stellar atmosphere is irradiated by the soft X rays emitted from the flaring loop filled with the hot plasma. This radiation heats a large area beneath the loop. Subsequent cooling due to H^- and hydrogen free-bound emission can contribute to the observed enhanced continuum.

Estimate of the Maximal Possible Flare Energy in a Given Active Region (AR)

The maximal possible total energy of a flare that may happens in a given active region (AR), arriving from the photosphere into the corona of AR, can be etimated accordingly to Livshits et al. (2015).

So, the free energy is $E_{free} = E - E_{pot} = R/8\pi \int \left((B_{t,pot})^2 - (B_t)^2)\right) ds$, where the tangential components of the observed B_t and potential $B_{t,pot}$ fields under condition that $B_n = B_{n,pot}$ in each point, R is a radius of a sphere in spherical coordinates.

For calculation of the free energy one use here observations and the calculated values of the potential field on the photosphere without NLFFF extrapolation (nonlinear force-free field). We have applied one of NLFFF extrapolation algorithms and the virial theorem to data of the vector of the magnetic field of a solar AR.

The solar experience shows us that the free energy is spent portionwise and every large flare "devours" 10–15% of the free energy Efree deposited in this AR.

For non-stationary processes on the Sun, the maximal flare energy is $E_{max} = 3 \times 10^{32}$ erg (Livshits et al., 2015).

The mean longitudinal magnetic field of fast-rotating young G stars $|B_l|$ is around 5 G (as it follows from the results of "Bcool collaboration" by Marsden et al., 2014). This is 10 times stronger than that on the Sun at the maximum of the cycle, if we compare with the present day-Sun: the averaged over the Carrington rotation the magnetic field of the Sun as a stars at high activity level (for example, in 1980), $|B_l|$= 0.5 G.

Then maximal possible flare energy of young G stars E_{flare} is propotional to B^2 and can not exceed $\sim 5 \times 10^{34}$ erg. The stronger events require for their explanation, either non-solar analogies for the origin of flares or changes to the dynamo mechanism (Katsova et al. 2018).

What can confirm the solar-type mechanism for stellar superflares?

The first point is detection of the hard X-rays in stellar flares, till now the sensitivity is not enough, although recently launched mission SPECTR-RG with the eROSITA could be helpful. The next step is registration of microwave bursts at the maximum of a flare: if we adopt that the total number of injected accelerated electrons is $N = 10^{38}$ per/s, the heating flux $F = 3 \times 10^{11}$ erg/cm^2 s and flare area $S_{opt} = 4 \times 10^{18}$ cm^2, then the microwave flux of such a superflare on the star at the distance of 100 pc is estimated as 2 mJy Katsova & Livshits (2015). Under favourable monditions such a value can be detected.

The third point is detection of lithium production by spallation reactions during stellar flares: (6708 A line). There are the only two theoretical estimates by Livshits (1997) and Ramaty et al. (2000) for the appearance of a large amount of Li and its diffusion over the surface during some big solar flares. On the Sun, Livingston et al. (1997) observed the Li I line during 4B Solar Flare of 9 March 1989. Then Li I line enhancement during the big flare on a late-type star observed by Montes et al. (1998). Besides, Flores Soriano et al. (2015) observed chromospheric activity and lithium line variations in the spectra of the spotted star LQ Hydrae.

Some exotic scenarios for giant stellar flares with energies $> 10^{35}$ ergs:

It is clear that we are now far from understanding of the physics of such a powerful non-stationary phenomenon on "normal" stars. Such events are unpredictable, and at present there is no reasonable model of the largest stellar superflares due to an obvious flaw observational data in different spectral ranges. Therefore it is possible now the only to mention a few unusual directions where success or disappointment can be expected.

An avalanche model, proposed for solar flares, suggested that during an interaction of flares in parts of activity complex or several nearby active regions. The avalanche can, perhaps, provide a superflare. This approach was applied for small-scale structures by Osokin et al. (2004).

One more possibility for very Young Suns, where superflares can be associated with evolution of large-scale magnetic fields: some evidences for existence of quadrupole component of the magnetic field in these stars do exist. Then it may resemble the process of global reconstruction of a whole corona. The first step of it may be observed as a prolonged superflare.

Another unusual way is a model for the largest flares suggests emergence of flux rope in large-scale potential field as suggested by Török et al. (2014).

Specific dynamo models

Unfortunately, hydrodynamics of Kepler's stars with superflares with $E \sim 10^{36}$ erg unknown and can differ significantly from the solar case. These can be young fast rotating stars or components of binary systems where activity does not depend on rotation and is in saturated regime.

Stellar dynamo is able to generate not only cycles, but also stationary configurations. Numerical modelling shows that this is realized in a case of anti-solar differential rotation. In this case the power of dynamo does not spend on reversal (change of the sign of the magnetic field), and its energy becomes significantly higher.

There is a scenario which allowed us to understand how stellar dynamo can create the magnetic field whose energy exceeds significantly that of the Sun (Katsova et al. 2018).

The sign of dynamo sources of stars with superflares normally can be opposite to the solar case. A change of the sign of the dynamo number D can be due to anti-solar differential rotation or, possible, to anti-solar sign of the mirror-asymmetry of stellar convection (the sign of the parameter α (the rate of recovery of the toroidal magnetic field from the poloidal one due to cyclonic motions as compared to the Sun).

5. CONCLUSIONS

Steallar superflares with $E = 10^{33} - 10^{34}$ erg can be consired as an analog of the solar events with effective particle acceleration.

Most of Superflares with $E > 10^{35}$ erg occur on young, fast rotating stars at the saturated activity epoch, and subgiants and/or components of close binary systems as well.

This epoch of the highest level of the coronal activity ($\log L_X/L_{bol} = -3$) is characterized by independence of this activity tracers on rotation. Namely in these stars non solar–type steady dynamo with anti-solar differential rotation and/or opposite sign of the dynamo number can be realized. This is a way how to get a magnetic configuration with substantially higher magnetic energy compared with the current solar case.

Stellar cycles form on stars in unsaturated regime of solar-type activity when oscillating dynamo does turn on. This occurs for G, K and M stars at various rotation periods.

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