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Estimating the Energy of Solar and Stellar Superflares

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Abstract—We discuss the current observations of the most powerful non-steady phenomena on solar-like stars. While remaining within even the most extreme solar ideas, it is very problematic to get the flare energy more than (3–5) × 10^{34} erg, which is apparently an absolute upper limit for solar-type flares. For explanation of the higher flare energy, about of 10^{36} erg, one need to adopt that spots with the magnetic field strength of a few kG should cover more than 30% of a hemisphere. This estimate leads to a mean magnetic field around 1 kG. New observational evidences for a presence of the strong magnetic fields on solar-like stars appeared recently. We discuss to what extent it is necessary to change the mechanisms of convection and dynamo with a corresponding change in the models of the atmosphere. We consider possible ways of solving the problem of the energy of superflares.

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1. INTRODUCTION

The superflare concept applicable to powerful non-stationary stellar phenomena has been introduced when the first results of the Kepler mission operated in 2009–2018 with a detection of huge flares on G-type stars were published (Maehara et al., 2012, 2015). They reported on registration of large stellar flares on solar-like stars with the total energies from 10^{33} to $>10^{37}$ ergs at optical wavelengths. Detection of superflares on low-mass stars during the Kepler mission became a challenge for astrophysics, as it raised the question of their reality in the present-day Sun. The total energies of solar flares from weakest events to the strongest ones span in the wide range 10^{24}–10^{32} erg. The more detail analysis showed that the total energies of the most of flares are 10^{33}–10^{34} erg, while only a small fraction of these phenomena can be considered as superflares with the higher energies, up to ~10^{35}–10^{36} erg. Later on it became clear that the most powerful events with $E > 10^{36}$ erg occur either on very young, fast rotating active stars, which can be both members of the young open clusters and pre-main-sequence T Tau-type stars, and components of chromospherically active RS CVn-type close binary systems as well. The total energies of the strongest of stellar flares on these stars can exceed values of $\geq 10^{36}$ erg in the optical spectral range (Katsova and Nizamov, 2018; Okamoto et al., 2021).

Note that prior the Kepler mission, there was very little information about flare activity of solar-like stars, because single G dwarfs are too bright for ground-based observations, and it is difficult to observe unpredictable and rare flare phenomena without regular monitoring. For example, the powerful white-light flares from pre-main sequence stars associated with the Orion complex of an average age about of 4.0 Myr, were detected during ground-based observations as part of the Next Generation Transit Survey (NGTS)—the project dedicated to wide-field exoplanet survey at the Paranal observatory in Chile (Jackman et al., 2020). From an analysis of 83 stars Orion-associated stars which were observed with NGTS, these authors found 26 flares from 17 stars in 7 months of monitoring. The only one star among them belongs to the spectral type G3, the rest 16 of these 17 flare stars had spectral types from K to M3. The observed flares had energies ranging between 6.7 × 10^{33} and 5.2 × 10^{35} ergs. Such large flares are some of the most energetic white-light flare events seen to date.

Avaliable estimates of sizes for several strong stellar flares in optics, derived from colorimetric observations on the best studied red dwarf star EV Lac,

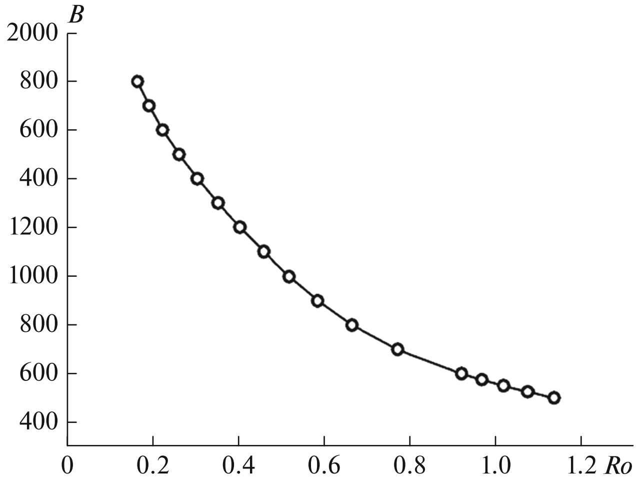

Fig. 1. The magnetic field strength, *B*, versus the relative distance in the spot, covered by the field above the threshold value in real spots, *Ro*.

showed that their sizes can exceed those of typical solar white-light flares by a factor of 10 and 30, and in some cases up to 120 (Lovkaya, 2014; Alekseev and Gershberg, 1997).

An analysis of multiwavelength observations of stellar flares and other non-steady phenomena on red dwarfs and solar-like stars gives evidences for their common physical nature to solar ones (Gershberg and Pikel'ner, 1972; Gershberg et al., 1987, 2020). This is about a deposit of the free energy of the non-potential magnetic field in a certain volume, its impulsive release during non-steady process, a subsequent response of the atmosphere to arising acceleration particles and plasma heating. At the same time, already Gershberg et al. (1987) paid attention to the unsatisfactory of modern models of solar flares for explanation the strongest stellar flares.

2. AN ACCUMULATION OF THE FREE ENERGY FOR GENERATION OF SOLAR FLARES

Traditionally, the total energy E, required for a flare can be calculated as follows $E = FB^2L^3/8\pi$, where F is a portion of the free energy, deposited in a given active region, which is spent in a flare. Essentially, it is supposed that the magnetic field is enclosed in a volume with characteristic dimensions L, and it is constant there. The factor F shows that the only non-potential fraction of the field dissipates. The estimate of F is extremely difficult to obtain and uncertain. Livshits et al. (2015) give values of a few percent (no more than 10–15%) based on the results of extrapolation of magnetic fields on the Sun in the nonlinear force-free approximation. Assuming that $B = 3000$ G and $L = 3 \times 10^9$ cm, we get $\sim 3 \times 10^{32}$ erg.

This value is close to the energy evaluation for the most powerful solar flares and this situation could be satisfactory. However some parameters in these calculations are overstated and, in any case, significantly differ from statistical properties of the largest sunspots. E.g., the magnetic field in a spot very rarely reaches 3000 G. The maximum sunspot field, at least as recorded in the past decades, is on the average 2050 G (Livingston et al., 2012; Livingston and Watson, 2015). But even this value was only recorded in a small area at the very center of the umbra. The characteristic size $L = 3 \times 10^9$ cm is also overestimated. It is by no means the size of the shadow. This value corresponds to a large active region rather than a spot.

3. EVALUATION OF THE MAGNETIC FIELD STRENGTH AND THE STRUCTURE IN SUNSPOTS AT THE PHOTOSPHERE LEVEL

The sunspot is an area of an enhanced strength of the magnetic field. However, so far there is no reliable data on the magnetic field strength on a boundary of the spot. This value is very important, because namely it determines a decrease of the convective heating of the photosphere occurs this as well as an appearance of the dark formation. It is difficult to measure this value due to the irregularity of boundaries and difficulties in drawing isolines. This is even more difficult to do this on high-resolution magnetograms. Therefore we proposed a new approach—calculation of area in which the field is above a certain threshold (Obridko and Shelting, 2018). Then the threshold value at which the total "magnetic" area coincides with the total spot area measured on that day can be called the spot boundary.

We used daily SDO/HMI data on a longitudinal component of the magnetic field during 2375 days from May 1, 2010 to October 31, 2016. Daily sunspot number data were taken from the site WDC-SILSO, Royal Observatory of Belgium, Brussels http://sidc.oma.be/silso/datafiles (version 2). The total daily values of sunspot areas were adopted in NASA site https://solarscience.msfc.nasa.gov/greenwch.shtml.

It turned out that the spot boundary corresponds to the magnetic field value of 550 G. The stronger magnetic fields above 2000 G occupy an extremely small part of the spot, no more than 20%. The field falls off rather quickly with distance from the center of the spot (Fig. 1).

The mean value **B** is around 750 G for the smallest spots, it increases slightly up to 900 G in those days, when the total spot area on the Sun is 500–2000 msh, and then grows up a little more. This value seems rather small, but it should be taken into account that the main contribution here comes from penumbra, which occupies about 80% of the sunspot area (Bludova et al., 2014). It is not easy to highlight here the average field values in the total umbrae of the spots,

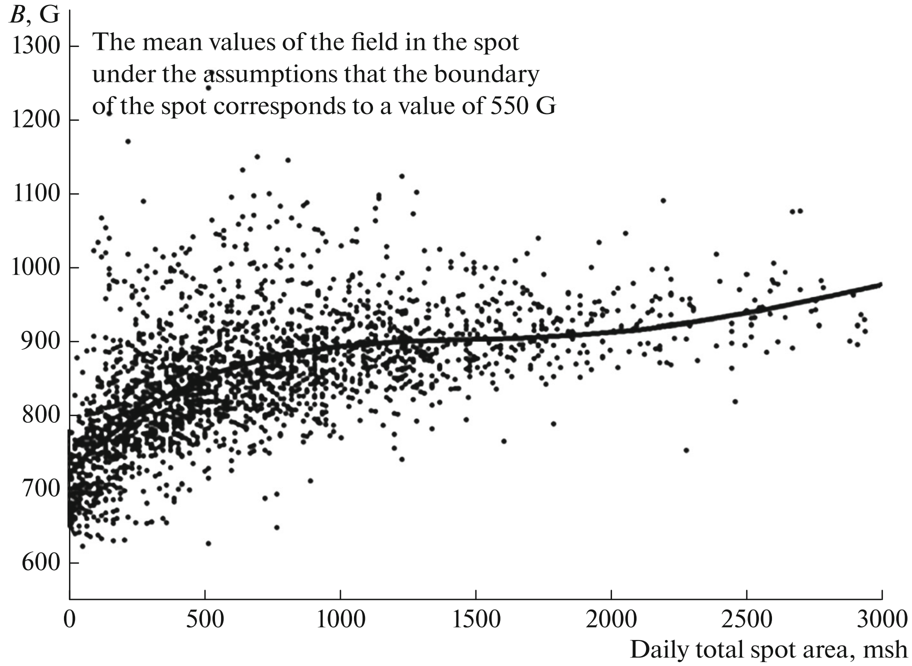

Fig. 2. The mean magnetic field strength values in spots.

since the magnetic boundary of the umbra is even more undefined than the **visual** boundary of the umbra. The photometric boundary of the umbra (i.e., the inner boundary of the penumbra) is usually more blurred than its outer one. Based on the relative umbra area, it can be assumed that the boundary of the umbra corresponds to the magnetic field strength of 1000–1100 G. The mean field values in the spot umbrae under such assumptions are shown in Fig. 3.

Thus, the average field values in the sunspot umbra are 1400 G and also weakly depend on the area. These values obtained look rather low compared to the average value given in (Obridko and Nagovitsyn, 2017), which was 2050 G, and it was obtained from the results of the 1957–1997 database http://www.gao.spb.ru/database/mtbase/. It should be noted, however, that the purpose of these observations was mainly to find the maximum field value for each spot.

In this case, the relative fraction of the area of the umbra is about 20% and very weakly decreases with the spot area (Fig. 4).

It is much more difficult to estimate the height at which the reconnection zone L_z is located. According to various estimates, this should be the lower corona with a density $n_e \sim 3 \times 10^8$ cm^{-3} or somewhat more. The geometrical height of this area can vary significantly. It is higher in undisturbed region (5000–7000 km) and is lowered over the spot to values of the order of 1–2 thousand km. Some observational values can be used to estimate the magnetic field at this altitude (see Obridko, 1985, and references therein). The field gradient falling with height may be less than 0.7 G/km at different spots. This means that one can expect the field of about 1000 G at an altitude of 1–2 thousand km above the sunspot.

Thus, evaluating the energy stored in the flare region should be calculated on a more complicated formula $E_{\text{flare}} = SL_zB^2/8\pi$, where S is a flare area, B is volume-averaged field strength. For the above values in a very large spot (although not the largest one) with an area of 1000 msh and an average field value of 1400 G and a height of $L_z = 10^8$ cm, we obtain 1.2×10^{32} erg, which is also close to the observed values for the most powerful solar flares.

However, it should be noted that our calculations were guided by the averages rather than the maximum values observed in the past. Let us now estimate the energy that would correspond to the simultaneous appearance of all extreme parameters. The largest spot groups reach an area of 4000 msh (Aulaner et al., 2013). For the entire time of observations of the magnetic fields of the spots, 55 active regions were registered, with a magnetic field above 4000 G. Note that these "superfields" occupied an extremely small effective area in active regions. Finally, recently, based on observations of SDO/HMI and Hinode SOT/SP by calculations of a force-free magnetic field, a magnetic field of 4000 G was found at an altitude 10^8 cm (Anfinogentov et al., 2019). Assuming that the average field is 4000 G over the entire area of 4000 msh, we get $E = 8 \times 10^{33}$ erg. This value can be considered as the absolute upper limit for the energy of solar flares. Note

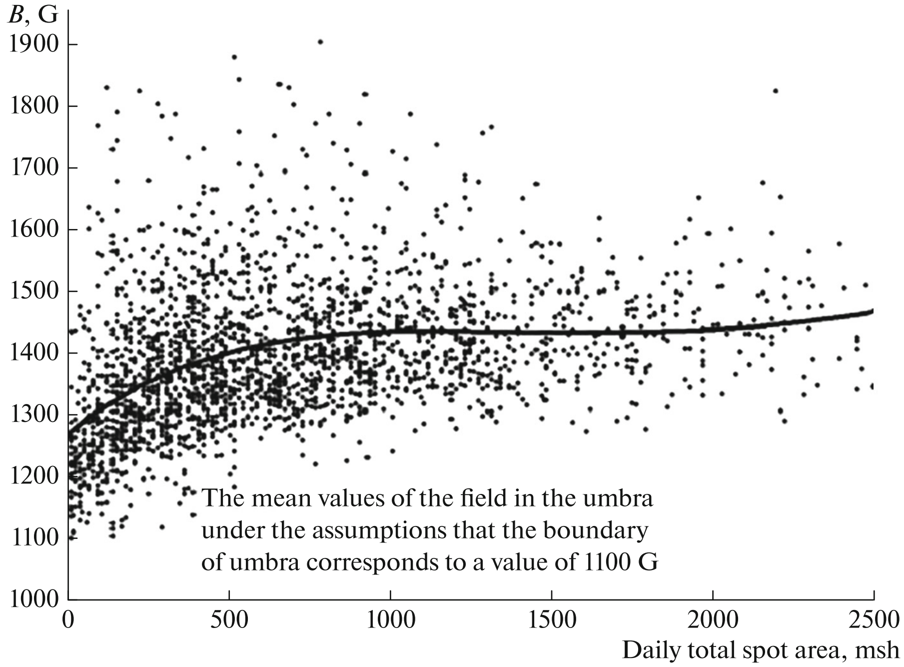

Fig. 3. The mean values of the field in the umbra. The line presents the approximation by the 4th degree polynomial.

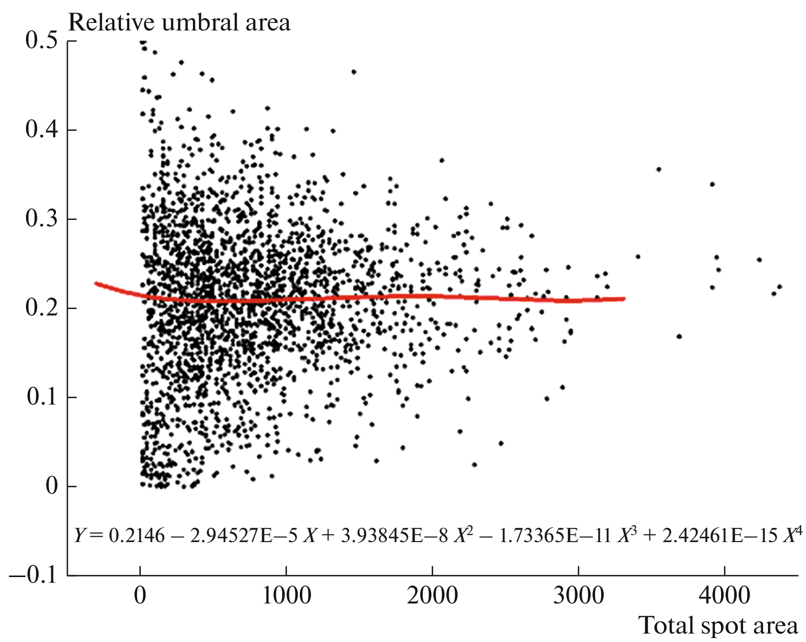

Fig. 4. The relative fraction of the umbra area versus the total spot area, msh.

here that, of course, the adopted size corresponds not to the spot area, but to a rather large active region.

4. ON THE ENERGY OF STELLAR SUPERFLARES

Let us consider the possibility of accumulating energy sufficient for stellar superflares with energies up to 10^{36} erg. In this case, we will be guided by the already used concept of the similarity of flares on the Sun and stars, mentioned at the beginning of the article, and the second expression for the energy in the previous section. It is necessary to change the parameters of the star so as to obtain $E = 10^{36}$ erg. Since we assume that we are dealing with a solar-like star, the characteristics of the corona should be the same. As a consequence, the dependence of the density in the corona should be preserved and, accordingly, the value of B_z changes a little. The most promising is to increase the area. But, it is impossible to increase the area by 4 orders of magnitude, the average area of a large spot (300 msh) limits our capabilities. If we allow an increase by a factor of 1000, then the spotted area should be 0.3 of the hemisphere. This value agrees with estimates starspot areas on low-mass stars including young Sun analogues (Alekseev and Gershberg, 1996; Livshits et al., 2003). In this case we get the energy of 3×10^{35} erg, which in principle is already enough. The rest can be added by a slight 10% increase in the remaining parameters.

However, the difficulties/problems did not disappear, but moved to another plane. In fact, the mean magnetic field at such a star will be 1–2 kG, which is not observed. There is no way to avoid this sad conclusion. You can try to increase the L_z, but it's not much help. An increase in L_z means that the flare occurs at heights of a few tenths of the star's radius. Any strong magnetic field at this height is impossible. In addition, such star should exhibit considerable variability in the magnetic field strength with amplitude 800–1200 G, brightness—10% and several times in EUV—and microwave range. A spot of such a huge size should lead to a decrease in the average brightness by 20–25% and a certain change in the spectral type towards the K-type. A region of strong overheating should appear under such a spot. There is such an area under the sunspot, but there heat diffuses into the lateral regions and comes out to the surface in the form of a light ring surrounding the sunspot. There will be nowhere to diffuse. In the subsurface layers, convection will be stopped over a large area. It is not yet clear, how the dynamo will operate under such conditions and whether it is compatible with the generation of strong magnetic fields. However, it is possible that recent observations of magnetic fields on the young solar twins (Kochukhov et al., 2020) can be understood as an indication of the possibility of just such a stellar dynamo operation. Apparently, such a dynamo must operate directly on the surface of the star, so that a hypothetical spot, occupying almost the entire surface of the star, should be continuously regenerated by the dynamo mechanism. A powerful coronal condensation should appear over such a giant spot, and such stars should have very strong ultraviolet, X-ray and radio emission.

Talking of the mean field when estimating the flare energy, we must have in mind a field that occupies a sufficiently large area of the star and is accessible to low-resolution observations. Of course, a significant part of the magnetic flux on stars (as well as on the Sun) is contained in small-scale features. However, to estimate the released energy, it is necessary to sum up the areas of all these small elements. Besides, we must assume that the flare energy is released simultaneously or in a finite time in these spaced elements. In any case, this picture differs significantly from the generally accepted model of a solar flare.

The duration of the solar and stellar flares could not fit on one line. These distributions of solar and stellar flares cannot be explained by the same power-law relationship, and the durations of superflares are an order of magnitude shorter than those extrapolated from the power.

Thus, formulated more than 30 years ago (Gershberg et al., 1987), the difficulties not only failed to overcome, but with the availability of new data matching problem of solar flares and stellar superflares become even more acute. Despite the similarity of general physical manifestations, it must be admitted that there are significant differences either in the mechanisms of magnetic field generation, or in the main flare model, or in both.

5. DISCUSSION AND CONCLUSION

In our opinion, the main message from recent observational evidence that superflares with energies substantially higher rather than ones known for solar flares can occur at the stars with physical properties not very remote from the solar ones can be formulated as follows. Solar dynamo cannot be considered as the only model for dynamo action on various stars. Observational evidences concerning superflares means that a moderate variation of solar dynamo drivers can result in excitation of magnetic configuration with substantially different physical properties rather solar ones. It is naturally to believe that the dynamo active shell responsible for such magnetic configuration should be located immediately below stellar surface.

Note that the above discussed difference between solar and stellar spots already discussed in scientific literature (e.g. Mullan et al., 2006, Namekata et al., 2017, 2019) however a possibility to consider corresponding stellar dynamos in the framework of solar ones was discussed. We believe that now the results accumulated are sufficient to indicate substantial difference of these stellar dynamos with solar one.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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