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Parameters of Superflares on G-Type Stars Observed with the Kepler Space Telescope

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Abstract—We continued the analysis of 279 G-type stars with superflares (energies in the range of 10^{33}–10^{36} erg). We calculated the SFL parameter (part of the stellar surface which emits in the flare). The SFL estimates were derived from the relation connecting this value with the amplitude of the flare and its radiation on the assumption of the blackbody character of the emission at times close to its maximum. Most SFL values are in the range of 0–0.1, with values of 0.2–0.4 for some strong flares. Dependence of SFL on effective temperature for stars with superflares is similar to that found earlier for the spottedness parameter S. The SFL distribution reaches its maximum in the temperature range of about 5100–5250 K and decreases with the effective temperature increase. We suggested an assumption on the presence of bimodal distribution in the "SFL–rotation period" relation with a gap for objects with rotation periods P of about 10 days. For stars with P less than 10 days, the given data can indicate a decrease in flare areas with the P increase. Our analysis showed that significant changes both in flare energy and in flare areas can be achieved with small changes in spottedness S for one and the same star.

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1. INTRODUCTION

In the present study, we continued the analysis of the properties of active regions of 279 G-type stars, on which more than one and a half thousand superflares with energies in the range of 10^{33}–10^{36} erg were discovered.

Based on the observed data from [1], we have estimated earlier [2] that high surface spottedness is characteristic of the stars with superflares, which should be considered as evidence of their high magnetic activity. Independent determination of the luminosity of these stars [3] allowed us to confirm this conclusion. Analyzing the same data [3], we concluded that in spite of high spottedness, stars with superflares do not stand out with the parameters of differential rotation $\Delta\Omega$ in the whole array of stars.

In [4], we studied diagrams which connect superflare energies and the parameters of stellar activity (areas of their magnetic spots) and conducted more extensive studies of activity of two stars with the record number of flares. As a result, we have shown that the variation range of stellar superflare energies (up to two orders) is fullfilled for the whole interval of their rotation periods. An assumption was made on the bimodal data distribution in the "superflare energy–rotation period of the star" diagram. In the "superflare energy–area of cold spots" diagram, three groups of stars were distinguished which differ in surface spottedness areas. An assumption that flare activity is not connected directly with circumpolar active regions was confirmed. It is seen from the analysis of stars from the sample, which includes the objects with more than 20 superflares, that considerable energy variations (up to two orders) can be attained for one and the same star with small variations of spottedness S. We detected considerable spottedness variability (5–6 times) for the two objects from our sample (KIC 10422252 and KIC 11764567). The increase of flare energy by orders was observable for these objects at any level of spottedness. Lastly, the detail analysis of activity was carried out for the two stars, KIC 11551430 and KIC 11764567, with all available photometric measurements from the Kepler archive data. The record number of flares (one flare per 7 days on average) have been detected earlier for KIC 11551430; KIC 11764567 has the greatest number of flares (one flare per 25 days on average) among the stars with rotation periods comparable to the Solar one. Using the constructed maps of surface temperature nonuniformities of the stars under study,

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we determined the longitudes and other characteristics of active regions.

Our calculations of spottedness S provided the opportunity to fulfill the number of additional comparisons of parameters of stars with superflares [4]. Moreover, the data from [1] allow us to estimate the SFL values (relative area of stellar surface which show emission during a flare). One can find the estimations of these values for flare stars in the literature (see [5, 6] with references). In [6], possible reasons have been indicated for which these estimations are of interest, chiefly, for comparing the flares with each other, for determining the heating mechanism, etc.

2. CHARACTERISTICS OF SUPERFLARES ON SOLAR-TYPE STARS

In a detailed study of flare stars, the analysis of simultaneous spectral and photometric (broadband and in white light) observations [6] are possible. The methods developed in such studies allow one to consider numerous additional factors (see [6]) which are unavailable for us; thus, analyzing the observed data obtained with Kepler (without multicolor photometry), we will have to confine ourselves to the simplest estimations. Let us note that such estimations were used earlier at the initial stages of flare-star studies (see [5, 7]).

The flare area SFL expressed in fractions of the visible stellar surface can be obtained from the simple relation connecting this value with the flare amplitude and its emission (on the assumption of the black-body character of flare emission at times close to its maximum):

$$\mathrm{SFL} = (k-1)\,\frac{F_{\mathrm{star}}}{F_{T_{\mathrm{BB}}}},$$

where k is the normalized amplitude of a flare.

According to [5–7], emission at the flare maximum is of a black-body character and is characterized with the temperature T_{BB}. For flare stars, T_{BB} is determined from color charts. As far as analyzing the Kepler observed data we are derived of this opportunity, T_{BB} can vary as a parameter. In the study of flare stars (see [7]), the flux from the undisturbed object photosphere F_{star} can also be estimated in the black-body approximation. However, for the stars under study, we used the flux estimations derived with the Kurucz models from the effective temperature estimates given in [1]. Obviously, the calculated energy distributions need to be checked with consideration of effective transmittance of all the instruments (for the Kepler mission in our case, they are the telescope and detector with the spectral band from 400 to 850 nm). The similar relation for estimating the flare area from observations of the star EV Lac in the U filter is given, e.g., in [7], where they have obtained the estimate of the flare area as 1.1% of the visible stellar surface with the temperature $T_{\mathrm{BB}} = 18\,500$ K and effective stellar temperature EV Lac 3300 K. Moreover, the relation similar to ours was considered in [1], and the value 10 000 K was assumed for the temperature T_{BB} and the energy of superflares was estimated.

Using the presented relation on the assumption of the temperature $T_{\mathrm{BB}} = 20\,000$ K with the data from [1] about 1547 flares, we derived SFL for 279 solar-type stars with superflares. According to our estimation, most of the SFL values are within the interval 0–0.1 attaining 0.2–0.4 for some intense flares. Figures 1a and 1b show the dependences of the flare areas SFL and, for comparison, cold spot areas S on the surfaces of the studied stars on their effective temperature T_{eff}.

We analyzed the distribution of the spottedness parameter on T_{eff} earlier in [2] and concluded on the high spottedness of stellar surface of the stars with superflares (their higher magnetic activity). The S distribution (Fig. 1b) attains its maximum within temperatures 5100–5250 K and decreases with the effective temperature increase. The object that stands out with S greater than 0.3 is the star KIC 7174505 [1]; its properties will be reviewed in other study (after the detailed analysis according to the methods presented, e.g., in [8–11]). The view of the SFL distribution (Fig. 1a) over T_{eff} is, by its nature, similar to the determined distribution for S. Figure 1c shows the relation of the parameters SFL and S. Despite the considerable range of their variations (from 0 to 15–20), the great majority of data indicates that the relation values are within the range of 0.3–0.8 with possible insignificant increase of these values for hotter stars.

It can be inferred that flare areas (for many events) are equal to about half the area of spots within the simple model we assumed for $T_{\mathrm{BB}} = 20\,000$ K. This inference is fairly conditional: for instance, if we take the parameter $T_{\mathrm{BB}} = 10\,000$ K, then the considered relation will be in the range from 2 to 6 (the flare areas significantly surpass spot areas).

Figure 1d shows the SFL values that we obtained depending on the period of axial rotation of stars P. One can suppose possible bimodal distribution for the diagram data with the gap for objects with P equal to about ten days in the same way, as we did it in [2] analyzing the similar dependence for S. As was noticed in [2], owing to the fact that the data for objects with periods longer than ten days is relatively small, there is no answer to the question if maximum flare areas of the stars with rotation periods smaller than ten days are similar to those greater than ten days. If the stars with P smaller than ten days are only considered (Fig. 1e), then the data given can

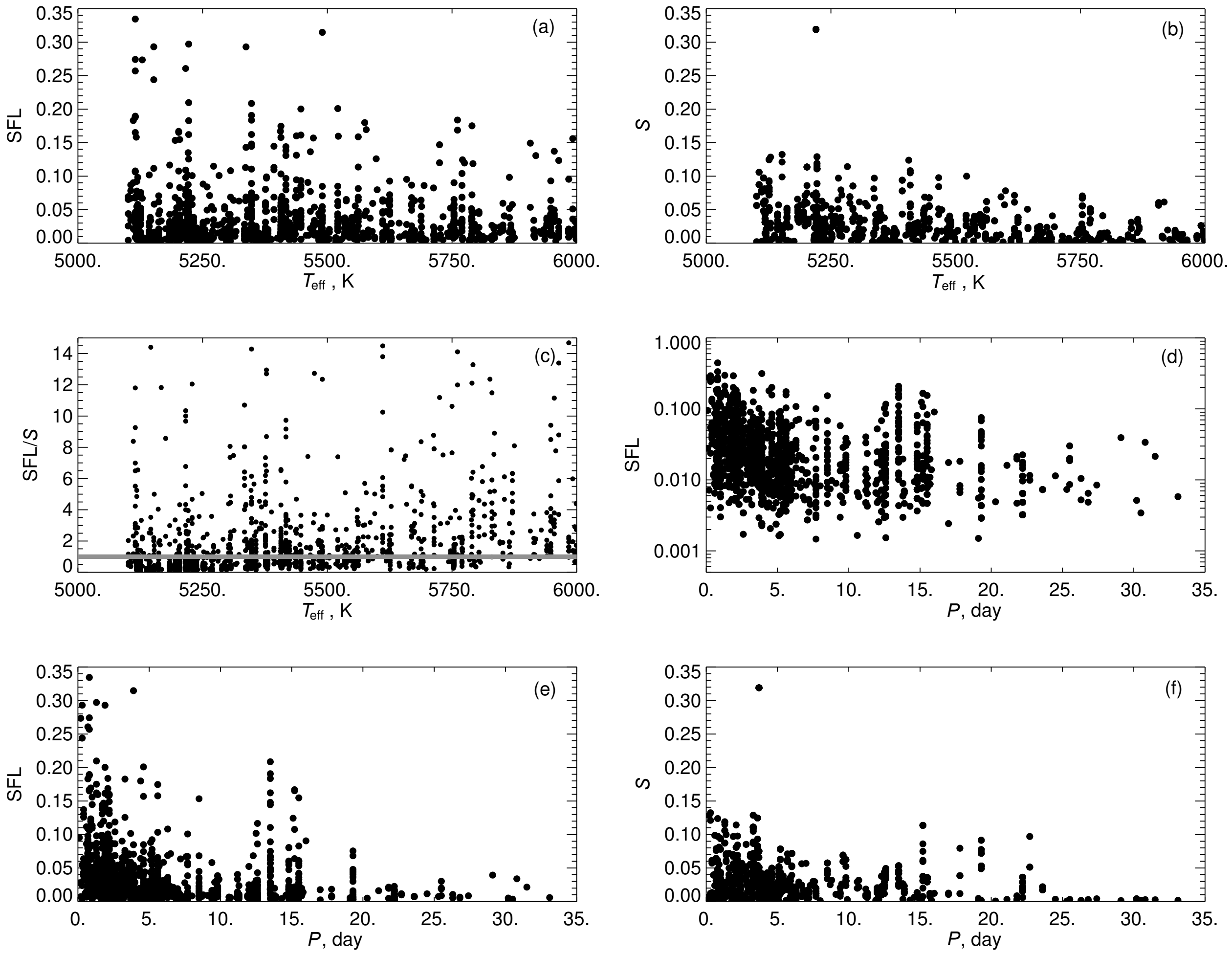

Fig. 1. Distributions over effective temperature: (a) of the flare areas SFL and (b) the cold spot areas S on the surfaces of the studied stars, (c) of the relation of the parameters SFL and S (the solid line corresponds to the relation equal to 1). (d, e, f) The values SFL and S depending on the period of axial rotation of the stars P; in diagram (d), the ordinate axis is given in the logarithmic scale. The object that stands out with S greater than 0.3 is the star KIC 7174505.

indicate the decrease of flare areas with the P increase (similarly to the S parameter, Fig. 1f).

Finally, Fig. 2 illustrates the comparison of S and SFL. It would be natural to expect definite correlation between these values, however, it does not follow from the results of our calculations based on the data from [1]. On the contrary, it can be inferred that for the same star, along with small variations of S, one can observe both considerable variations of flare energy (see [2, 4]) and the variations of flare areas. With practically similar spot areas, the flare energies and their areas can vary up to two orders. It seems important to check this conclusion with other data sets apart from [1], as soon as such data are available.

3. DISCUSSION OF THE RESULTS

As in the case of investigation of flares on late-type stars (colder than our Sun), the analysis of superflares on solar-type stars can start out only from solar analogies (the data on flares which were thoroughly studied with the use of ground-based observations and numerous special cosmic missions). Along with this during solar and stellar flares, emission in the lines and continuum is detected from the X-ray to radio wavelength ranges. The considerable portion of emission arrives in the blue and near infrared wavelength ranges; it is often called white-light emission.

Drawing an analogy with the Sun, the authors of many studies (see, e.g., [6, 12]) suppose that flare regions on flare stars are associated with the complex of arcades of successively closed magnetic loops. The flux of non-thermal electrons originated from the magnetic loops reconnection reaches the lower atmosphere and leads to emerging the emission in the lines and continuum. A large number of emitting regions increases the duration of flares. Thus, according to [1], several tens of objects had flares lasting longer than 0.2 days and the white-light megaflare on the

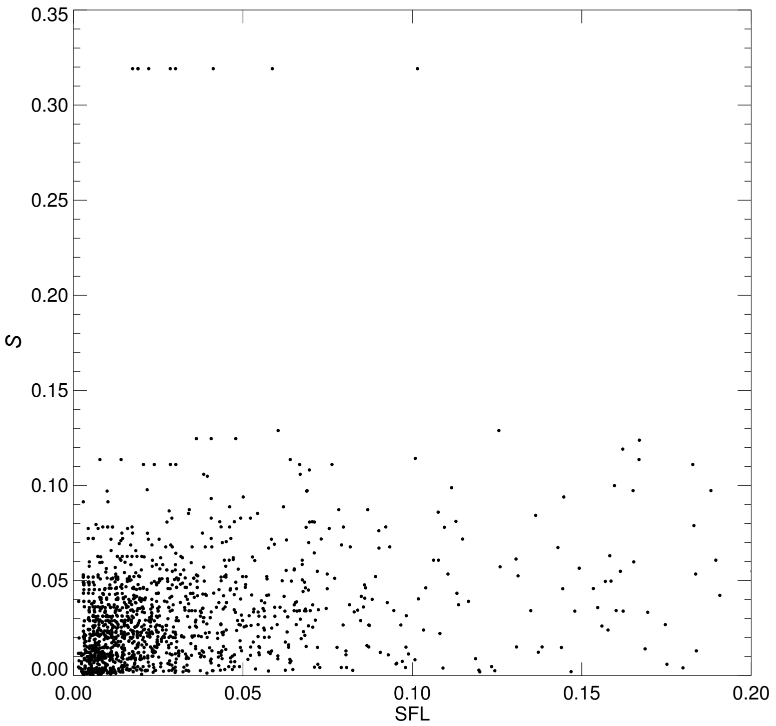

Fig. 2. Comparison of S and SFL. The object that stands out with S greater than 0.3 is the star KIC 7174505.

dM4.5e dwarf star YZ CMi lasted for more than seven hours [12].

Spectral observations of flare stars showed that the flare emission can be considered in the first approximation as the sum of two components: the black-body emission (BB) and the emission in the Balmer continuum (BaC) and in lines. It was shown for relative filling factors of these components that the emission in the Balmer continuum comes from regions that have larger areas (from flare loops reaching the chromosphere level). In the spectral range with wavelengths greater than 400 nm, the emission is of black-body type (apparently, it is exactly the component that is detected in monochromatic observations of solar-type superflares with the Kepler space telescope). The BB component probably forms at the bottom of flare arcs in the lower atmosphere. In the case of studying the megaflare on the dM4.5e dwarf star YZ CMi, Kowalski et al. [12] determined that the BB emission emerges in the regions that are 3–16 times smaller in size that the regions of the BaC emission formation, moreover, anti-correlation between the emission intensity of these components appears with time. The BB emission temperature in the megaflare on the star YZ CMi was about 10 000 K according to estimates from [12]. By estimate in [7], the BB emission temperature in the flare on the star EV Lac attained 18 500 K. The available monochromatic observations of superflares on solar-type stars with Kepler do not allow us to estimate the emission temperature of the black-body component (and the presence and contribution of the BaC component also). Estimating the flare areas, we found that, with $T_{\rm BB}$ equal to 20 000 K, the flare areas amount to about half the area of spots. Supposing, as in [1], that $T_{\rm BB}$ is equal to 10 000 K, then the flare areas will exceed the areas of cold magnetic spots. It is obviously important to derive the most accurate estimates of flare and spot areas: thus, for example, in [1] the estimates of flare energies are based on the SFL estimates; in [13] the estimates of magnetic energy accumulated in magnetic elements and released in flares are also based on the estimates of sizes of magnetic regions.

4. CONCLUSIONS

We continued the analysis of properties of active regions (cold spots) on the surface of 279 G stars, on which more than one and a half thousand of superflares were discovered with energies in the range 10^{33}–10^{36} erg. We calculated and compared the spottedness parameters S and the SFL parameter (the fraction of stellar surface that emits during the flare).

The following results are obtained:

(1) The SFL estimates are found from the relation connecting this value and the flare amplitude with its emission under the assumption on the black-body character of the emission at times near its maximum. We derived SFL for 279 solar-type stars with superflares from this relation under the assumption

on the temperature $T_{\rm BB} = 20\,000$ K with the data on 1547 flares from [1]. By our estimates, most of the SFL values are within the interval of 0–0.1 attaining 0.2–0.4 for some intense flares.

(2) The dependence of SFL on the effective temperature of stars with superflares is similar in character to the dependence for spottedness that we have determined earlier. The distribution of SFL attains its maximum in the temperature range of 5100–5250 K and diminishes with the effective temperature increase.

(3) Within the model we assumed with $T_{\rm BB} = 20\,000$ K, the flare areas are equal to about half of the area of spots for most objects (with the spread in values of the relation SFL/S up to 8–10). If we accept $T_{\rm BB} = 10\,000$ K, then the considered relation will be within the limits from 2 to 6 (i.e., the flare areas exceed the spot areas).

(4) The assumption was made on the presence of bimodal distribution with the gap for objects with a period of about ten days for the data in the diagram “SFL–rotation period P”.

(5) Our analysis showed that with small S variations for the same star, the variations of flare energy (flare areas) can be considerable. It seems important to check this conclusion with another data set, aside from [1].

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