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Activity and Cold Spots on the Surface of G-Type Superflare Stars

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Abstract—Based on the high precision photometric observations of the Kepler space telescope, we have investigated the properties of the active regions (cold spots) on the surface of 279 stars of the spectral class G, for which 1547 superflares with energies in the range of 10^{33}–10^{36} erg have been revealed. The main conclusion of our study is the quantitative estimation of the increased surface spottedness of superflare stars, which indicates enhanced magnetic activity of these objects. The increased spottedness on the surfaces of the studied stars was confirmed based on two independent estimations of stellar brightness variations. In addition, it was concluded that superflare stars do not stand out in the common dataset of differential rotation parameters. Based on the data considered, no correlation was found of the spottedness parameters or the differential rotation parameters with the characteristics of these objects—their Rossby numbers and superflare energy. Additionally, the correlation between the superflare energy and the inverse Rossby number was considered. None of these comparisons gave an indication for the presence of any obvious correlation. The results of the analysis of five stars with a few dozen flares registered indicate that for the same star whereas spottedness S variations are small, significant changes in the superflare energy can be achieved. On the example of KIC 10422252, we show that at sixfold S variations, the flare energy varies by orders of magnitude at any given S value.

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1. INTRODUCTION

From the analysis of the data for 148 spectral type G stars observed by the Kepler space telescope, Maehara et al. [1] have discovered 365 superflares (flares with energies of 10^{33}–10^{36} erg are commonly called the superflares). This study for the first time allowed researchers to obtain statistical estimates of superflare parameters for G dwarfs and to establish that the estimates of the superflare occurrence rate distribution as a function of their energy are similar to the estimates obtained for the Sun. Furthermore, Maehara et al. [1] found that the G dwarfs they studied have spots on the surface, observable in the rotational modulation of stellar brightness. Flare occurrence frequency with energies of about 10^{33}–10^{35} erg in sunlike stars (across the sample of studied objects) has to be on average one event every 800–5000 years. Not a single planetary system was found in the studied sample of superflare stars. This conclusion is extremely challenging, because it was earlier believed [2] that G dwarfs with hot Jupiters rotating around them are good candidates for superflare stars.

Shibayama et al. [3] later extended the study of Maehara et al. [1] and from the Kepler space telescope observational data made an analysis of 1547 superflares for 279 stars of spectral type G. They considered the observational data covering the time interval from May 2009 to September 2010 (observational sets Q0–Q6) with a total duration of about 500 days.

The results of [3] also indicate the power-law distribution of the flare occurrence frequency, similar to that found for the Sun. In the study of long-term brightness variability (over approximately 500 days) [3] it has been found that for a number of objects the flare rate can be very high; in particular, for KIC 10422252 it was 57 superflares in 500 days (i.e., one flare every 10 days). Shibayama et al. [3] also note that there are indications that the stars they have studied have large spots on the surface—they believe them to be ten times larger than the solar spots—and that the physical nature of high frequency and the very occurrence of superflares are associated with the presence of large spots on the stars.

The aim of our study is to explore the properties of active regions (cold spots) on the surfaces of superflare stars. The technique of analysis of photometric observations that we have developed [4] allows us to determine based on periodic variability of stellar brightness caused by its rotation the presence and properties of active regions (spots) on the surface

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of stars and consequently the characteristics of their magnetic activity. Based on the results of application of this technique to the superflare stars, we have tried to find an answer to the question of possible distinctive properties of their magnetic activity.

Investigation of magnetic activity of superflare stars on the one hand gives ample opportunities to test the developed models of magnetic field generation and the models of superflares in the G-type stars. On the other hand, it will serve as a basis for determining the effect of flares of such energy on the medium surrounding them (the analogue of space weather formation in our Solar System). Notice that solar flares, even with energies of less than 10^{32} erg, can lead to significant variations in the state of the Earth's atmosphere. High-strength geomagnetic storms similar to the Carrington event in 1859, the March 13, 1989 storm, etc. might be a source of dramatic disruptions and blackouts.

2. OBSERVED DATA AND ANALYSIS

Based on the high-precision photometric observations obtained by the Kepler space telescope, we have earlier [5] examined the properties of the active regions (cold spots) on the surface of 737 stars with planetary systems with measured rotation periods and reliably determined atmospheric parameters. We have examined three methods for determination of the spottedness of stellar surfaces from photometric observations: based on solving the inverse problem of reconstructing the surface temperature inhomogeneities of stars from their brightness curves [6], within the simplified procedure proposed in [4, 7], and, finally, by the relation presented in [7] (S is determined as the ratio of the area of all spots on the surface to the area of the entire visible surface of the star).

It was shown that the method proposed in [7] and modified by us in [4] can be applied to a large enough sample of objects and, most importantly, it yields homogeneous data which can be used for statistical estimation and finding dependencies of general nature. This very circumstance has allowed us, using the brightness variability data for 34 030 objects from [8], to find the S parameters, which will be used below with respect to the features of the distribution of the S parameter on the effective temperature for different objects.

Based on this, we used the specified technique in the analysis of activity of the the 279 stars in which Shibayama et al. [3] have reported 1547 superflares. For this purpose, we used the data of Table 2 from [3], which contains information both about the photometric variability of these stars and their flare activity.

3. ACTIVE REGIONS AND DIFFERENTIAL ROTATION

Figure 1 presents the main results of our study. The upper part of the figure contains the diagram of the dependence of spottedness S (the value which can be considered as an indicator of magnetic activity) of stars with observed superflares on the effective temperature $T_{\rm eff}$ of these objects. For convenience of comparison with the data shown in Fig. 3 of [8] and the figures from our previous research [5], the y-axis in Fig. 1 is represented in the logarithmic scale. For comparison, just like in [5], we have presented the S parameters that we found for 34 030 stars from [8]. We have discussed the features of the distribution of the S parameter depending on the effective temperature in [5]. The main of these features is that the upper envelope of the S values reaches its maximum at temperatures of about 5400 K and sharply drops in the region of high temperatures (6000–6500 K). The lack of objects with effective temperatures of about 4500 K and 4000 K (they correspond to stellar masses of $0.55\,M_{\odot}$ and $0.7\,M_{\odot}$), notable from the results of [8] and beginning to take shape in Fig. 1, is an artifact caused by the temperature calibration of the Kepler catalog data. The lack of objects in the domain of cool stars makes it impossible to distinguish the bimodal character of variability distribution in cool stars [8]. The lack of cool stars with small S (small amplitude of photometric variability) noted in [8] is quite noticeable. It was found in [5] that the data we obtained for the stars with exoplanets demonstrate similar characteristics, noted by McQuillan et al. [8] and more conspicuous for their sample of 34 030 objects. The main conclusion of [5] is that we have not found any features that would distinguish the magnetic activity of stars with exoplanets from the activity of stars from a larger sample of [8].

For the superflare stars the analysis of distribution of the spottedness parameter depending on $T_{\rm eff}$ leads to the following conclusions. The distribution of S apparently also reaches its maximum around temperatures of about 5400 K and decreases with increasing effective temperature. At low $T_{\rm eff}$ the absence of objects with temperatures of less than 5100 K does not allow us to draw definite conclusions about the behavior of the S parameter. In the $T_{\rm eff}$ range from 5100 K to 6000 K, the lower boundary of the S distribution probably coincides with the corresponding boundaries for 34 030 objects from [8] and stars with planetary systems [5]. At the same time, it is obvious that the upper boundary exceeds them. We can consider this circumstance as a direct indication of increased spottedness of the surfaces of superflare stars and, accordingly, their increased magnetic activity. This conclusion can be regarded as the main result of our study.

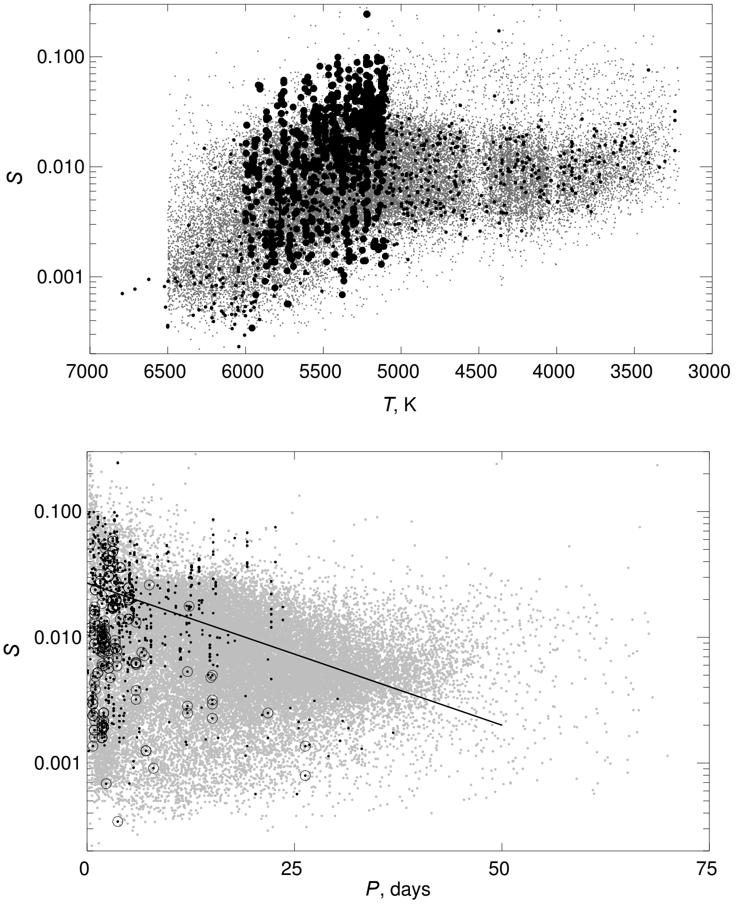

Fig. 1. Top: the dependence of spottedness S of superflare stars on the effective temperature $T_{\rm eff}$. The values of S are expressed in fractions of the total visible surface of the star. The S parameters that we found for 34 030 stars from [8] are shown by gray characters, where the stars with exoplanets are marked by small circles, and superflare stars are depicted by large circles. Bottom: the dependence of stellar spottedness S on the rotation period. The S values are fractions of the total visible surface of the star. The S parameters that we found for 34 030 stars from [8] are shown by gray characters, the data for the superflare stars with effective temperatures of less than 5750 K and exceeding 5750 K are marked with the black dots and the contoured dots respectively. The solid line describes the dependence from [8] of spottedness S on the rotation period for stars with exoplanets and effective temperatures of less than 5750 K (see the text).

Research of objects with exoplanets [5] allowed us to take a new look at the diagram of the dependence of the spottedness parameter on the stellar rotation period. Investigation of a complete sample of 34 030 stars indicates complexity of the rotation period dependence of the S parameter, which is represented by a set of dependencies and groupings of objects in the "S–rotation period P" diagram. Figure 1 (bottom) demonstrates a full array of these objects in gray color. Specifically, for the stars with exoplanets, in [5] it was found that in the case of stars with effective temperatures of less than 5750 K, there is a prominent dependence of the spottedness on the period of rotation (monotonic decrease of S up to the periods of 35–40 days). This relation is described by the solid line. In addition, an important result of our study [5] is that among the stars with effective temperatures below 5750 K and rotation periods of less than ten days, no stars were found with small S (less than 0.002). On the contrary, stars with effective temperatures exceeding 5750 K demonstrate very low spottedness in the case of rapid rotation (short rotation periods), which increases for objects with rotation periods of about 20–25 days. The analysis of the data, presented in Fig. 2, corresponding to the superflare stars has shown the following. Firstly, the data for the objects with rotation periods P of less than 25 days with a large scatter satisfy the main dependence described by the solid line (stars with P exceeding 25 days probably lie below it). Secondly, among the stars with P of less than ten days for the whole temperature range, there are both stars with small and large spottedness parameters. Finally, among rapidly rotating stars with effective temperatures exceeding 5750 K, there are stars the

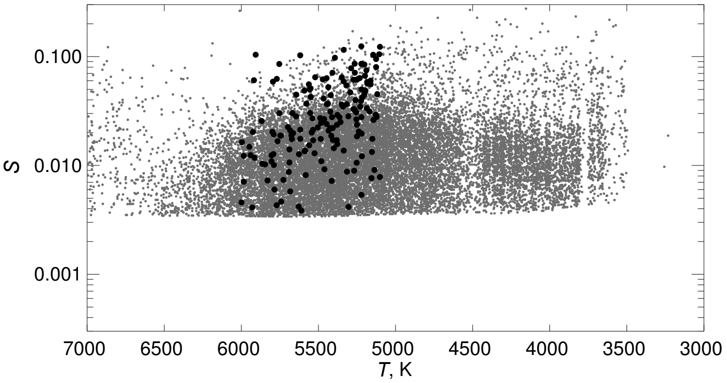

Fig. 2. Dependence of spottedness S of superflare stars (according to [9]) on the effective temperature $T_{\rm eff}$. The S values are expressed in fractions of the total visible surface of the star. The S parameters that we found for 34 030 stars from [8] are marked by gray characters, and those for the superflare stars from [9] are indicated by the black circles (see the text).

area of spots in which exceeds 1%, although in general most of these objects (contoured characters) lie below the main dependence. Obviously, the features of the S parameter dependence on the rotation period of superflare stars do not exactly follow the features that were previously identified in stars with exoplanets.

4. ESTIMATES OF THE SPOTTEDNESS AND DIFFERENTIAL ROTATION ACCORDING TO REINHOLD, REINERS, AND BASRI

Apart from the possibility of finding stellar rotation periods from the brightness modulation due to the presence of cold spots on the surface, high-precision observations of the Kepler space telescope also allow us to establish the presence of the differential stellar rotation. For example, Reinhold, Reiners, and Basri [9] have determined the rotation periods of more than 40 thousand active stars based on the observations during Q3. For a large number of these objects (18 616 stars, 77% of the total number) the presence of the second period close in value was determined. Considering the existence of two periods as a result of differential character of stellar rotation, Reinhold et al. [9] have estimated the following parameters of differential rotation: $\Delta\Omega$ (the difference of the angular velocity at the equator and at the pole) and α—the relative parameter of the differential rotation law of the following form

$$\Omega(\theta) = \Omega(\mathrm{eq})\,(1 - \alpha\sin^2(\theta)),$$

where θ is the latitude. Recall that for the Sun $\alpha_{\odot} = 0.2$.

Analyzing the data from [9], we found that among the 18 616 estimates of the differential rotation parameters found in this study, 165 belong to the superflare stars.

This dataset was primarily used to determine the S parameter. The analysis of the data from [9] allows us to confirm the conclusion about the increased surface spottedness of superflare stars obtained from independent determinations of brightness variability of these objects in [3]. Figure 2 shows the distribution of the S parameters, found for 18606 stars based on the brightness variability estimates performed in [9] for the Q3 observation period. Notice that unlike McQuillan, Mazeh, and Aigrain [8], Reinhold et al. [9] have only considered the dwarfs with increased variability (the $R(\mathrm{var})$ parameter exceeding 0.3%). But even in this sample, the data on S for 165 superflare stars indicate an increased spottedness of these objects and confirm the above conclusion about their enhanced magnetic activity.

Figure 3 gives the distribution of the $\Delta\Omega$ parameter for 18 616 stars from [9], which characterizes the differential rotation of objects depending on $T_{\rm eff}$. It also highlights the results corresponding to the 165 objects common with the study of Shibayama et al. [3]. It follows from the present data that possessing increased spottedness, the superflare stars do not however stand out in any way from the general mass of stars by their differential rotation parameters.

5. DISCUSSION

The research of photometric variability of stars based on the observations of the CoRoT (see, e.g. [10]) and Kepler space missions (examples of our research in [4, 11–13], etc.) lead to new results that were previously essentially inaccessible for the observations with ground-based telescopes. These should also include the discovery of superflares with energies of 10^{33}–10^{36} erg in G-type stars. This discovery has for the first time allowed us to make statistical estimates of the superflare parameters for G dwarfs

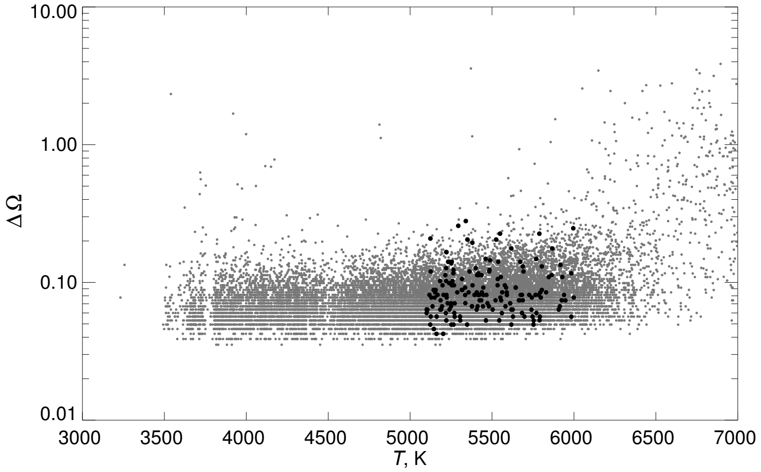

Fig. 3. Distribution of the $\Delta\Omega$ parameter, which characterizes differential rotation of the 18 616 stars from [9] (gray symbols), depending on T_{eff}. Dark circles mark the results corresponding to the 165 objects common with [3].

and to establish that the estimates of the distribution of superflare occurrence frequency as a function of their energy are similar to the estimates made for the Sun, and also to find that the studied dwarfs have spots on their surfaces, which manifests themselves in the rotational modulation of stellar brightness.

If just as in the case of the Sun we can consider the magnetic spots as one of the most typical indicators of stellar magnetic activity, then the increased values of the S parameter found in our study also indicate a relatively higher level of magnetic activity of superflare stars.

The data of Shibayama et al. [3] and our calculations gave an opportunity to make a number of additional comparisons of the parameters of superflare stars. Notice that none of these comparisons using a sample of objects from [3] gave indications of the presence of any obvious relations between the considered parameters. For control, in most of the given diagrams we mark the stars with effective temperatures exceeding 5750 K by individual characters.

Figure 4 shows a comparison of the spottedness S and differential rotation $\Delta\Omega$ parameters with the Rossby number $\mathrm{Ro} = P(\mathrm{rot})/\tau_c$, where τ_c is the duration of a convective revolution. Figure 5 compares the spottedness S and $\Delta\Omega$ parameters with superflare energies E. Figure 6 compares the superflare energies and the inverse Rossby number ($\mathrm{Ro}^{-1} = \tau_c/P(\mathrm{rot})$). The dashed line shows the statistical relationship from [14], proportional to Ro^{-1} and found from a broader sample of 795 stars (unfortunately, a detailed list of stars is not given by the authors), including not only the stars of spectral type G but also the K and M stars. Commenting on the nature of the found dependence, Candelaresi et al. [14] draw a conclusion that its statistical significance is small. There is no reason to believe that data from [3] satisfy this relationship.

We have selected five stars from Shibayama et al. [3] for which several dozen flares were registered. Record amount of flares (57) was found for the object KIC 10422252. Wu Chiju et al. [15], based on a broader set of the Kepler space telescope observational data later discovered 177 flares of this star. The largest number of flares (202) was found in [15] for the star KIC 11551430. However, the data from [3] attracted our interest most of all, as they allow direct comparison of flare energy with spottedness S measured at the same time. Figure 7 presents a comparison of S with superflare energies E (five different stars are indicated by different symbols). According to this figure (just like to Fig. 5), there is no dependence between the considered parameters. For the same star, at small variations of S significant energy changes can be achieved (i.e., at almost the same areas of magnetic spots, the flare energy can vary up to two orders of magnitude). The analysis of the data for the above-mentioned object KIC 10422252 can yield one more conclusion: the spottedness of KIC 10422252 during the period of observation (496 days) varied from 1% to 6% of the total surface of the star, and at the same time at any spottedness level, the flare energy variations reached orders of magnitude (10^{34}–5×10^{36} erg).

6. CONCLUSIONS

A study of 148 G stars in which Maehara et al. [1] discovered 365 superflares (energy in the range of 10^{33}–10^{36} erg), has for the first time made it possible to obtain the statistical estimates of the superflare parameters for G dwarfs. According to the later study

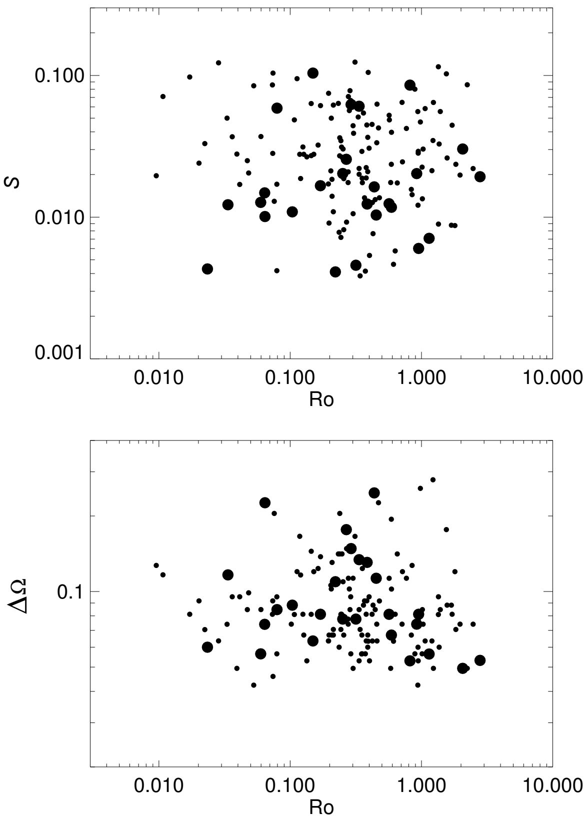

Fig. 4. Variations of the spottedness S and differential rotation $\Delta\Omega$ parameters depending on the Rossby number ($\mathrm{Ro} = P(\mathrm{rot})/\tau_c$). Large circles correspond to the data for stars with effective temperatures exceeding 5750 K.

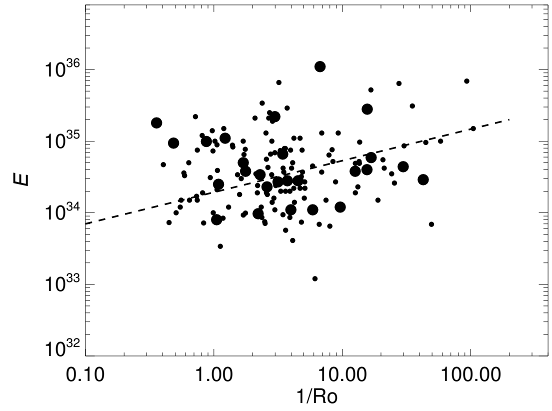

Fig. 6. A comparison of the superflare energy E (erg) with the inverse Rossby number ($\mathrm{Ro}^{-1} = \tau_c/P(\mathrm{rot})$). The dashed line shows the statistical relationship from [14], proportional to Ro^{-1} and determined based on a broader sample of 795 G, K, and M stars. Large circles correspond to the data for the stars with effective temperatures exceeding 5750 K.

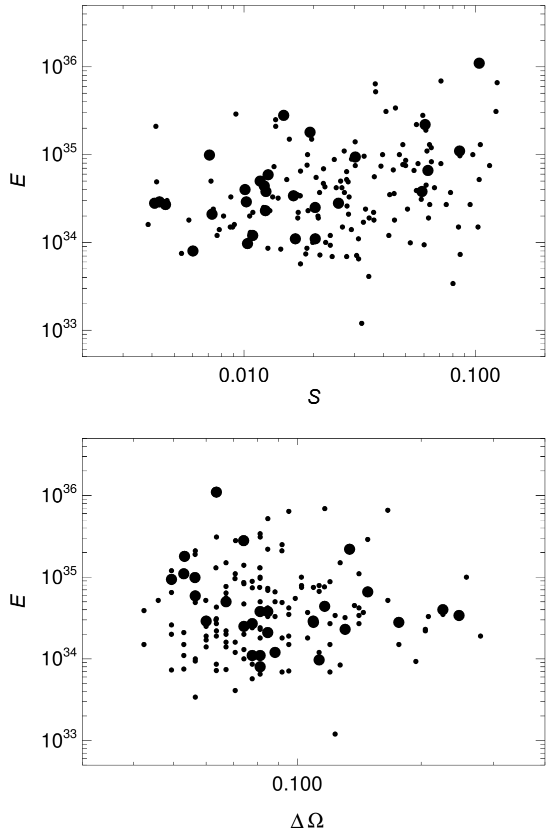

Fig. 5. Comparisons of superflare energies E (erg) with the parameters of spottedness S and differential rotation $\Delta\Omega$ (rad/day). Large circles correspond to the data for stars with effective temperatures exceeding 5750 K.

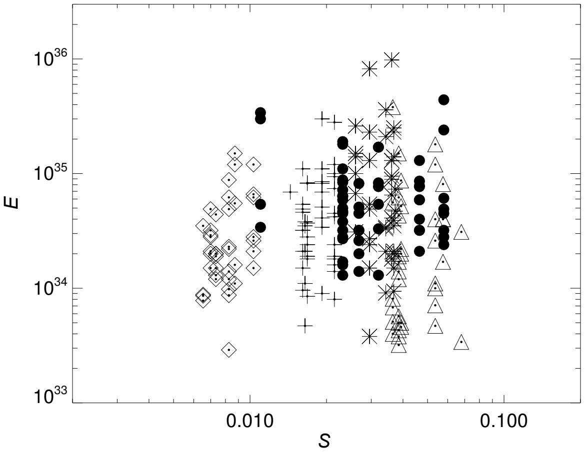

Fig. 7. A comparison of the superflare energy E (erg) and the spottedness parameter S for the five stars from [3]. Different stars are marked by different characters, dark filled circles represent the data for KIC 10422252 (see the text).

of Shibayama et al. [3], the conclusion of [1] on the power distribution of flare frequency to be similar to that found for the Sun has been confirmed. In studying a long-term brightness variability it was also demonstrated that for several objects the occurrence frequency may be very high. Both studies led to the conclusion that the stars being investigated possess large spots on the surface, significantly exceeding the sizes of the solar spots. Based on the high-precision photometric observations obtained with the Kepler space telescope, we have examined the properties of the active regions (cold spots) on the surface of 279 superflare stars of the spectral class G. The main conclusion of our study is the presence of increased surface spottedness of superflare stars which, in turn, also indicates their enhanced magnetic activity. The analysis of the data from [9] allowed us to confirm from independent brightness variability estimates the conclusion about increased surface spottedness of superflare stars. The same data [9] indicate that despite the increased spottedness, superflare stars do not stand out from the total majority of stars by their differential rotation parameters.

We compared the spottedness S and differential rotation $\Delta\Omega$ parameters with the Rossby number and superflare energies. The dependence of superflare energies on the inverse Rossby number was also considered. None of these comparisons, based on a sample of objects common for [9] and [3], gave any indication of the presence of any obvious patterns.

We have analyzed the results for the five stars for which Shibayama et al. [3] reported several dozen flares. A comparison of spottedness S with superflare energies E has not revealed any relationship between the parameters considered. Moreover, whereas S variations are small, significant energy variations could be attained for the same star, and in the case of KIC 10422252, which shows sixfold spottedness S variations, flare energy variations by orders of magnitude were registered at any S value.

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