Superflares and Starspots: when size does not matter

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Article

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Superflares and Starspots: when size does not matter

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Abstract

Within the last decade, space missions have provided a wealth of information about stellar flares. Nevertheless, what triggers these superflares, and whether they are similar to the solar counterparts, remains a great mystery. How are flares connected to active regions and what are the main causes of their occurrence? Here we investigate the activity of two K-type stars, similar in every way from mass to rotation periods and planetary systems. Even if both stars exhibited hundreds of spots, Kepler-411 produced 65 superflares, while Kepler-210 presented none. The spots of both stars were characterised using the planetary transit mapping technique which yields the intensity, temperature, and radius of starspots. The only discrepant parameter was the size of the spots. While the average radius of spots on Kepler-411 was $\mathbf{(17 \pm 7) \times 10^3}$ km, for Kepler-210 the mean radius was $\mathbf{(39 \pm 18) \times 10^3}$ km. That is, the star with no superflare exhibited spots twice as large as the the one with 65 superflares. Thus starspot area appears not to be the main culprit of superflare triggering, but rather the magnetic complexity seems more important, as in the case of the Sun. These are important clues to the magnetic dynamo acting on these solar type stars.

Keywords: Superflares, Starspots, Stars

1 Main

Solar activity phenomena reveal the structure of underlying magnetic fields and provide valuable constraints for solar dynamo theory [6]. Among the various solar phenomena, coronal mass ejections and flares are specially interesting due to their major impact on our planet and space weather.

Solar flares are transient phenomena that occur in the solar atmosphere in regions of high magnetic field concentrations, where large amounts of energy are released in the corona by reconnection of magnetic field lines [5]. Intense solar flares occur in active regions associated with sunspots of complex magnetic structure (e.g [11, 14, 23, 29, 40, 41]).

High precision photometric observation, such as that of the Kepler space mission [13], allowed detailed analysis of magnetic activity phenomena, such as starspots and faculae, superflares, and rotation of thousands of stars. During the first 120 days of Kepler observations, 365 superflares were detected with energies of 10^{33} to 10^{36} ergs in 148 G-type stars, of these 14 superflares occurred in stars similar to our Sun. The results further showed that stars with superflares exhibit an almost periodic brightness modulation, caused by the presence of large stellar spots on their surface. Thus, it is believed that flares in solar-type stars are also powered by magnetic reconnection, originating from extensive areas of active regions.

[30] report evidence that stars with superflares have extremely large stellar spots, about 10 times the size of the largest sunspot. Moreover, [22] investigated the relationship between the energy and frequency of superflares and the period of stellar rotation. The authors concluded that stars with relatively slower rotation can still produce flares as energetic as those of stars with faster rotation, although the average frequency of flares is lower for slow rotating stars. This same study emphasises that the energy of superflares is related to the total area coverage of starspots. The correlation between the stellar surface area coverage by spots and the energy of flares is similar to that of solar flares. Remarkably, these previous studies agree that the stars with larger spots tend to present more energetic flares, however [24] report that the strongest flares do not appear to be correlated to the largest starspot group.

Starspot analysis provide clues to stellar activity as well as better insight into magnetic dynamo models. Another important factor is the rotation period and how it changes with age [46]. From a polarimetry study of low-mass stars with ages from less than one Myr to over a Gyr old, [37] found that the average magnetic field strength in young stars is thousands of times stronger than that of main-sequence stars. This field difference means that the size and/or temperature contrast of cold spots on young stars, could be considerably larger than what is observed on their more evolved counterparts [9].

Currently, the great challenge is unveiling the mechanisms that cause superflares. On the Sun, we know that the most energetic flares tend to occur on large sunspots [27]. During the last decades, a large number of studies have revealed the nature of the processes that may influence flare occurrence on various time-scales, from the build up of energy to the trigger of flares. In their review, [35] cite as the main causes the magnetic complexity, new flux emergence, shear motion, sunspot rotation, and magnetic helicity injection. The authors conclude that magnetic complexity of active regions, such as that of δ spots, is more important than their size.

In other stars, due to the scarcity of data to infer how phenomena associated with the magnetic field behave, stellar flare studies rely instead on time-resolved photometry or spectroscopy [39]. For some time, it has been known that stellar flares are somewhat different from the standard solar model. Cooler than our Sun, stars such as the K and M dwarfs have flares that seem both surprisingly energetic (flares on active M dwarfs are typically 10–1000 times as energetic as solar flares) and qualitatively different from solar flares, showing strong continuum or "white-light" emission, which resembles a 9000–10000 K blackbody superimposed over the quiet spectrum of the star [39]. Flares in G-type stars follow the same pattern seen in K and M stars, however the flares are always more energetic and more frequent [4, 17, 22].

For the first time, two stars observed by Kepler will allow the investigation of the connection between starspots and superflares. One of the stars, Kepler-411 (K2V spectral type), exhibits intense stellar activity with spots and superflares, whereas the other star, Kepler-210 (also K-type) also has starspots albeit no superflare. In addition to being of the same spectral type (see Table 2), these stars also have similar rotation period and planetary systems.

Here, we present high spatial resolution spot transit modelling [31] of the two K-type stars with multiple orbiting planets. Small variations in the light curve during planetary transits are the signatures of the passage of a planet in front of a solar-like spot on the stellar surface [31]. This spot transit mapping model allows for high spatial resolution of spot's size, temperature, and location on the stellar disk. Thus providing clues about the explosive activity, or lack thereof, in these stars. Since these stars are transited by more than one planet, information about the spotted surface of these stars are obtained for more than one latitude.

Spot modelling of Kepler-411 has already been performed by [1] using the transits of the 3 exoplanets. The main parameters of the planets and their orbits are listed on Table 3. A total of 198 starspots were detected, and these are shown in maps of spot's longitude in time in Figure 3 of [1] obtained from each planetary transit. The spot's average size, intensity with respect to disk centre, and temperature are listed in the Table 1.

The spots of the star Kepler-210 were also modelled by applying the technique described in [31]. On Kepler-210, we were able to identify 236 starspots using the transits of the 2 exoplanets.

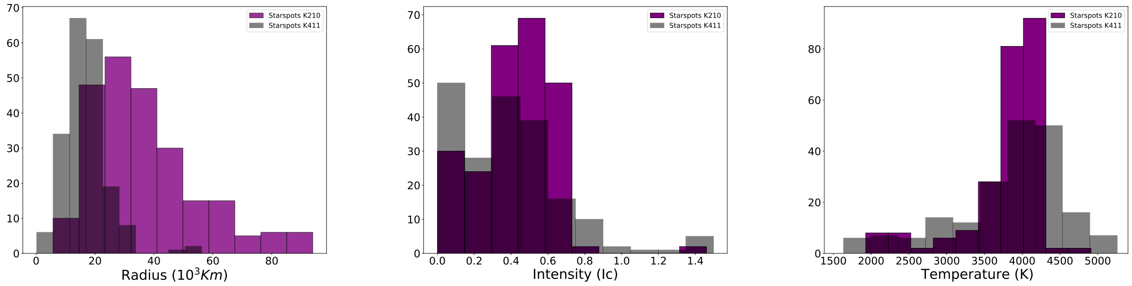


Fig. 1 Histograms of spot physical parameters: **Left:** radius, **Middle:** intensity with respect to surrounding intensity, I_c, **Right:** temperature. The grey histograms are for Kepler-411 spots, whereas the purple ones are for the spots on Kepler-210. The average value of these parameters are listed on Table 1.

Table 1 Physical parameters of spots

Parameter	Kepler-411	Kepler-210
Number of spots	198	236
Radius $[R_{star}]$	0.029 ± 0.012	0.078 ± 0.04
Radius $[10^3$ km$]$	17 ± 7	39 ± 18
Intensity $[I_c]$	0.35 ± 0.24	0.43 ± 0.22
Temperature [K]	3800 ± 700	3800 ± 500

Histograms of the spots parameters (intensity, radius, and temperature) are shown in Figure 1 for both stars, Kepler-411 in grey and Kepler-210 in purple.

The mean intensity of the spots can be converted to temperature by assuming that both the spot and the stellar photosphere emit as blackbodies [36]. From the measured intensities, the average temperature of Kepler-411 spots was estimated to be 3800±700 K, whereas those of Kepler-210 had mean temperatures of 3800±500 K. Since Kepler-210 has a slightly cooler surface temperature (T_{eff} = 4559 K) than Kepler-411 (T_{eff} = 4832 K), it is expected that the spots on Kepler-210 are a little bit cooler than those on Kepler-411. However the temperature of the spots from both stars can be considered as equivalent within the rms.

The surprising result found is the large difference in the size of the spots between the stars. The mean radius of spots on Kepler-411 are about (17±7) $\times$ 10^3 km, whereas those on Kepler-210 are on average (39±18) $\times$ 10^3 km.

Photometric modulations seen in stellar light curves, with periodicity of the stellar rotation, are usually associated with the presence of large spots that come and go into view as the star rotates. Several works claim that stars with larger spots present large flares [3, 16, 17, 21, 22, 43]. However, a few G-type stars, such as Kepler-17 [36] and the young star Kepler-63 [20], with clear evidence of many spots on their surface produced no detectable superflare on their light curve. For comparison, Kepler-17 spots have a mean radius of the order of (57×10^3) km, and Kepler-63 of $(32 \pm 14) \times 10^3$ km.

For the Sun, there are active regions that produce many flares, and on the other hand those that are flare-quiet [35]. The authors of this review discuss in depth three factors that may be responsible for flaring, the active region's (1) size, (2) magnetic complexity, and (3) evolution. Albeit the influence of the active region size, a more important factor is magnetic complexity such as that found in δ spots. The largest sunspot ever detected on the Sun (April 1947), with an area of 6136 MSH (or equivalent radius of 43.5×10^3 km), never produced a flare and was thought to have a β magnetic configuration [35].

Complex sunspot groups of mixed magnetic polarities, such as δ spots, associated to active regions are ideal locations for eruptive events such as flares or CMEs. Understanding flux emergence through the convective granular surface into the

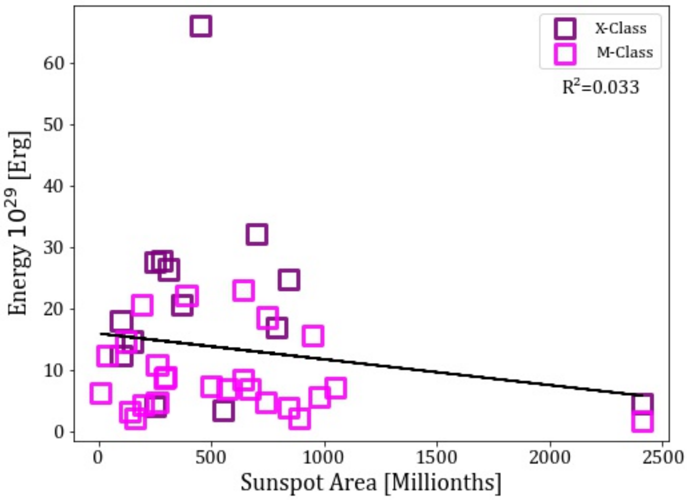


Fig. 2 Energy of 50 energetic white-light solar flares [19] of GOES class X and M as a function of the sunspot area of the active region where they occurred.

chromosphere and the associated sunspot magnetic topology and dynamics is thus key to better characterise solar activity [8].

From a study of flares more energetic than X1 (10^{-4} W m^{-2}) GOES class, [27] reports that 82% of these flares occur in δ spots, reaching 100% for flares larger than X4 (4×10^{-4} W m^{-2}), whereas only 24% of >X1 flares occur in big spots, with area larger than 1000 MHS (equivalent radius of 17.6×10^3 km).

To understand the relation between the area of active regions and flares, we analysed the 50 energetic solar white-light flares provided by [19]. The energy of these flares are plotted against the area of the active region where they occurred in Figure 2. As can be seen from the figure, no positive correlation is seen for these energetic solar flares.

Kepler data allows for a better understanding of the mechanisms associated with superflares. [26] proposed that superflares are caused by magnetic reconnection between fields of the primary star and a close-in Jovian planet. However, there is no evidence of this relationship in the stars studied by [16, 17]. And is certainly not the case for the planetary systems studied here, since all are planets are miniNeptunes or smaller.

[22] investigated the relationship between the energy and frequency of superflares and the rotation period of the star, taken as the periodicity of the light curve modulation. However, stars with relatively slower rotation rates can still produce flares that are as energetic as those of more rapidly rotating stars, although the average flare frequency is lower for slow rotators.

The intense magnetic activity represented by the presence of spots on the stellar surface could be an indication of a higher probability of superflare occurrence. But recent work on starspot modelling, such as in Kepler-17 [18, 36], did not detect any superflares, albeit an extensive number of large starspots. [15] investigated solar-type stars with large starspots, but found no superflares. For [18] the explanation for the absence of superflares in these stars is the simple magnetic complexity of the spots, being of type α or β, however direct observation of stellar magnetic configuration is not yet possible.

From Zeeman–Doppler imaging (ZDI), [28] determined the magnetic field topology of solar-type stars. The authors found that active stars presented a dominant average toroidal fields with large temporal variations, whereas the magnetic field of inactive stars was predominantly poloidal throughout their entire cycle. A poloidal magnetic field represents an axisymmetric field, whereas a toroidal field is non-axissymmetric. [7] argues that the difference in stars active cycle stars and inactive ones is the dynamo action at work. The stars in the active branch, with clear magnetic cycles have the dynamo mechanism acting in a shear layer near the stellar surface, whereas in inactive stars, the dynamo action takes place deep in the tachocline, the shear boundary layer between the radiative and convective zones.

The analysis of spots on the stars Kepler-411 and Kepler-210 resulted in different characteristics, specially about spot size. Kepler-210 spots are larger than Kepler-411 spots, more than twice the size. All other characteristics such as spot's temperature and stellar parameters of the two stars are fairly similar. Thus, our conclusion is that the difference in flare productivity lies in the spot size. However, what we found is contrary to previous reports in the literature, where a correlation between flare energy and spot area coverage of the star was found.

One explanation is that albeit large, the spots of Kepler-210 are of simple magnetic complexity (α or β), whereas those of Kepler-411 are of type δ, which may be more compact than α or β spots. A δ-spot can be formed in three different ways [35], all of which involves emergence of closely spaced different polarity spots, which invokes a dynamic flux tube emergence. Thus, the flare productive spots of Kepler-411 may be the result of a near surface dynamo action that produces predominantly toroidal field, whereas a deeper and slower dynamo is responsible for the larger and simpler β spots on Kepler-210, similar to the largest spot observed on the Sun. [28] find that the transition from stars with dominantly poloidal fields to stars with mainly toroidal fields occurs at a rotation of $\sim$12 days. We note that Kepler-411 has a rotation period of 10.4 days, whereas Kepler-210 rotates with a period of 12.33 days.

To expand the knowledge about stellar magnetic phenomena, this work investigated possible relations between stellar superflares and the physical characteristics of starspots. Two stars with similar physical parameters (mass, radius, T_{eff}, rotation) were compared to understand possible mechanisms of stellar magnetic activity manifested as spots and superflares. In the work of [1] positive correlations were obtained for the distribution of starspots and the energy of superflares in Kepler-411. We investigated whether the same phenomena occurred in another K-type star similar to Kepler-411. The same starspot modelling and superflares identification methodology was applied to the Kepler-210 star. Kepler-210 exhibited large starspots, but no superflares were detected. Thus, starspot area does not seem to be a main factor in the cause of superflares, but rather the magnetic complexity such as that found in δ sunspots.

We note that the main result presented here, that the size of the active region is not an important factor on flare occurrence, was only possible because of the spatially resolved analysis of starspots through transit mapping. Unfortunately, the current photometric data obtained with Corot, Kepler, and TESS is not able to decipher the magnetic complexity of starspots, difficulting the explanation of why some spotted stars produce superflares and others do not. Understanding stellar magnetic activity is important due to its direct impact onto the atmosphere of exoplanets and probability estimates of intense flares occurring on the Sun.

2 Methods

2.1 Data

Light curve data from the two stars, Kepler-411 and Kepler-210, were retrieved from the MAST website using PyKE routines from [38]. We used the 1 min short-cadence in Pre-search Data Conditioning (PDCSAP) format for our analysis. The two K-type stars are:

- **Kepler-411** (KIC 11551692) is a K2V-type star located at a distance of 153.6±0.5 pc exhibiting characteristics that indicate relatively strong magnetic activity [33]. Four small exoplanets orbits the star, with three of them transiting. Kepler-411 long cadence data are available on the MAST website for 17 quarters, and short cadence data for Q11 to Q17. Here, we use the short-cadence data in PDCSAP format for our analysis. The average rotation period of Kepler-411 is 10.4±0.03 days.

- **Kepler-210** (KIC 7447200) is a K-type active star, with two transiting Neptune-like exoplanets. The Kepler-210 data are available in the short-cadence format for the Q7-Q17 quarter.

Table 2 Stellar parameters of Kepler-411 and Kepler-210.

Parameter	Kepler-411	Kepler-210
Spectral Type	K2V[a]	K[c]
Radius [$R_\odot$]	0.820 ± 0.018^a	0.69^c
Mass [$M_\odot$]	0.870 ± 0.039^a	0.63^c
T_{eff} [K]	4832^b	4559^d
Period [days]	10.4 ± 0.03^a	12.33 ± 0.047^c
Distance [pc]	153.59 ± 0.48^a	234.33 ± 0.83^d
Number of flares	65	0

[a] [33]; [b] [10]; [c] [12]; [d] Exoplanet.eu

This star has an estimated average rotation period of 12.33±0.15 days [12].

We modelled the stellar spots on both stars using the [31] model, that was proposed for the first time to use an exoplanet as a probe to investigate the presence of spots on the surface of stars. From the spot occultation by a transiting planet, it is possible to physically characterise spots in solar-type (FGK) and M stars. This method requires high precision data, such as those obtained from the CoRoT, Kepler, and TESS space telescopes.

2.2 Physical Parameters of Starspots

The [31] model may be applied to light curves that have transiting exoplanets. First a 2D synthesised image of the star is constructed, considering limb darkening, and the transit of the planet in its orbit simulated. Also the model enables the inclusion of spots (dark) and faculae (bright regions) on the surface of the star. Again when a planetary transit is simulated, small "bumps" are seen in the transit light curve as the planets occults the dark spots on the stellar surface. Basically the height of this small flux variation is a measure of the spot's intensity whereas the duration of this bump reflects the spot's size. This method has been successfully applied to a few solar-type stars [1, 20, 32, 36, 44, 45].

This technique of spot transit mapping yields the physical parameters of the spots such as: size, intensity, temperature, and location (longitude and latitude) on the surface of the star. The temperature of the spot is obtained from the spot intensity fraction $f = \frac{I_{spot}}{I_{star}}$, with respect to the star's central intensity, I_{star}, by assuming that both the star and the spot emit radiation as blackbodies, following Eq.2 of [32].

2.3 Identification of Superflares

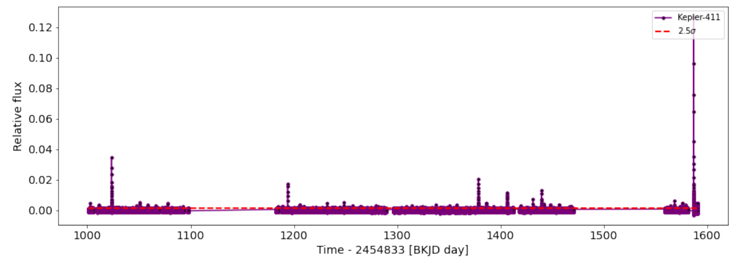
We carried out visual inspection of the light curves of Kepler-411 and Kepler-210, looking for impulsive brightness excess. We removed any indicator of data contamination according to Table 2–3 of [34], and then subtracted a high order polynomial so as to eliminate the spot modulation of the light curve with timescale of the stellar rotation period. The resulting light curves of both stars are shown in Figure 3, for Kepler-411 (top panel) and Kepler-210 (bottom panel).

A total of 65 superflares were identified in Kepler-411 light curve and have alredy been studied by [2]. The strongest flare produced by Kepler-411 is clearly seen at the very end of the observing period. However, no superflares were identified on the Kepler-210 light curve (bottom panel of Figure 3).

Table 3 Physical parameters of planets

Planetary Parameters of Kepler-411[a,b,c] and Kepler-210[d,e]					
	Kepler-411b	Kepler-411c	Kepler-411d	Kepler-210b	Kepler-210c
Orbital Period [days]	3.0051 ± 0.00005	7.834435 ± 0.000002	58.02 ± 0.0002	2.4532 ± 0.0007	7.9725 ± 0.0014
Planet Radius [$R_\oplus$]	1.88 ± 0.02	$3.27^{+0.011}_{-0.006}$	3.31 ± 0.009	3.08 ± 0.21	3.99 ± 0.14
Planet Radius [R_{star}]	0.024 ± 0.002	0.042 ± 0.002	0.040 ± 0.002	0.041 ± 0.002	0.053 ± 0.001
Semi-Major Axis [au]	0.049 ± 0.0006	0.080 ± 0.001	0.29 ± 0.0004	0.039 ± 0.001	0.070 ± 0.001
Orbital Inclination	89.18 ± 0.05	89.03 ± 0.02	89.44 ± 0.01	89.61 ± 0.26	89.28 ± 0.16

[a][42] [b]exoplanet.eu [c][1] [d][12] [e][25]



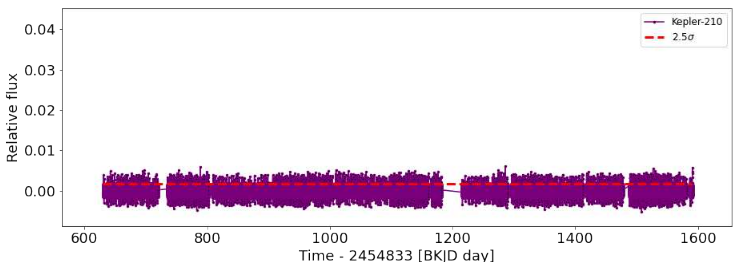


Fig. 3 Resulting normalised light curve after subtraction of high order polynomial for **Top:** Kepler-411 with the identification of flares and superflares, and **Bottom:** Kepler-210. The dashed red horizontal line in each panel represents the limit above 2.5σ of the average flux. To be considered a superflare, there has to be at least 3 points above the stellar flux indicated by the red dashed line.

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