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Superflares on solar-type stars

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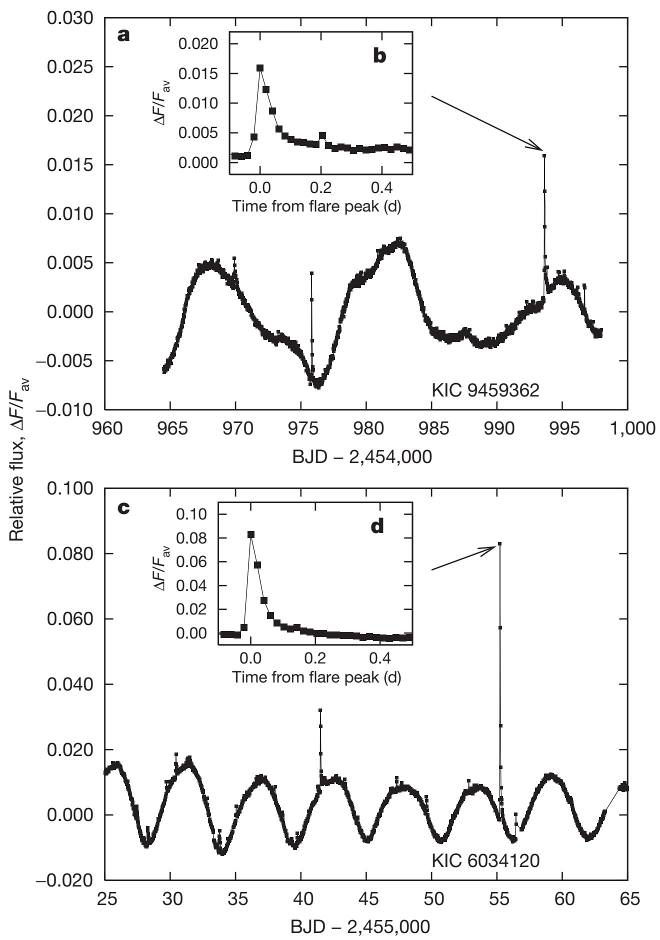
Solar flares are caused by the sudden release of magnetic energy stored near sunspots. They release 10^{29} to 10^{32} ergs of energy on a timescale of hours[1]. Similar flares have been observed on many stars, with larger 'superflares' seen on a variety of stars[2,3], some of which are rapidly rotating[4,5] and some of which are of ordinary solar type[3,6]. The small number of superflares observed on solar-type stars has hitherto precluded a detailed study of them. Here we report observations of 365 superflares, including some from slowly rotating solar-type stars, from about 83,000 stars observed over 120 days. Quasi-periodic brightness modulations observed in the solar-type stars suggest that they have much larger starspots than does the Sun. The maximum energy of the flare is not correlated with the stellar rotation period, but the data suggest that superflares occur more frequently on rapidly rotating stars. It has been proposed that hot Jupiters may be important in the generation of superflares on solar-type stars[7], but none have been discovered around the stars that we have studied, indicating that hot Jupiters associated with superflares are rare.



We searched for stellar flares on solar-type stars (G-type main-sequence stars) using data collected by NASA's Kepler[8] mission during the period from April 2009 to December 2009 (a brief summary of our flare search method is described in the legend of Fig. 1 and more detail is provided in Supplementary Information). We used the effective temperature (T_{eff}) and the surface gravity ($\log(g)$) available from the Kepler Input Catalog[9] to select solar-type stars. The selection criteria are as follows: $5{,}100\ \mathrm{K} \leq T_{eff} < 6{,}000\ \mathrm{K}$, $\log(g) \geq 4.0$. The total numbers of solar-type stars are 9,751 for quarter 0 of the Kepler mission (the length of observation period is about 10 d), 75,728 for quarter 1 (33 d), 83,094 for quarter 2 (90 d) and 3,691 for quarter 3 (90 d).

We found 365 superflares (flares with energy $>10^{33}$ erg) on 148 solar-type stars (light curves of each flare are summarized in Supplementary Fig. 8 and properties of each flare star are listed in Supplementary Table 1). The durations of the detected superflares are typically a few hours, and their amplitudes are generally of order 0.1–1% of the stellar luminosity. The bolometric luminosity and total bolometric energy of each flare were estimated from the stellar radius, the effective temperature in the Kepler Input Catalog, and the observed amplitude and duration of the flare by assuming that the spectrum of white-light flares can be described by blackbody radiation with an effective temperature of 10,000 K (ref. 10). We considered the spectral response of the Kepler photometer in doing our luminosity and energy calculations. The bolometric luminosity of superflares on G-type main-sequence stars ranges from 9×10^{29} to $4 \times 10^{32}\ \mathrm{erg\,s^{-1}}$, and the total bolometric energy of superflares ranges from 10^{33} to 10^{36} erg (hereafter the luminosities and energies of flares given are the bolometric values). The uncertainties in the luminosities and energies of flares are estimated to be about $\pm 60\%$.

Figure 1 | Light curve of typical superflares. **a**, Light curve of superflares on the G-type main-sequence star KIC 9459362. The individual points represent the difference between the observed brightness during each cadence and the average brightness during the observation period. The typical photometric error is about 0.02%. BJD, barycentric Julian date. **b**, Enlarged light curve of a superflare observed at BJD 2,454,993.63. The relative flux ($\Delta F/F_{av}$) and the duration of this flare are respectively 1.4% and 3.9 h, which correspond to a peak bolometric luminosity of $1.3 \times 10^{31}\ \mathrm{erg\,s^{-1}}$ and a total energy of 5.6×10^{34} erg. **c**, Same as **a**, but for the G-type main-sequence star KIC 6034120. **d**, Same as **b**, but for the superflare that occurred on KIC 6034120 at BJD 2,455,055.22. The relative flux and the duration of this flare are respectively 8.4% and 5.4 h, which correspond to a peak bolometric luminosity of $6.8 \times 10^{31}\ \mathrm{erg\,s^{-1}}$ and a total energy of 3.0×10^{35} erg. These superflares were detected by the following procedure. First we analysed the long-cadence calibrated flux (time resolution, 29.4 min) and calculated the distribution of brightness changes between all pairs of consecutive data points. Then the threshold of the flare was determined to be three times the value in the top 1% of the distribution. The threshold value is typically about 0.1% of the brightness of the star. Finally we defined as flare candidates those data points at which the brightness change exceeded the threshold. Because many of these flare candidates are false events (for various reasons), for confirmation we examined their durations and the shapes of their light curves, checked for the existence of nearby stars and studied the charge-coupled-device pixel-level data for each flare candidate.

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The brightnesses of the two stars in Fig. 1 show quasi-periodic variation. The period of the variation of KIC 9459362 is 12.5 d and that of KIC 6034120 is 5.7 d. The brightness variation can be caused by one of the following mechanisms: rotation of a star with starspots[11], orbital motion of a binary system[12], eclipse by an accompanying star[12] or stellar pulsation[13]. Here stellar pulsation can be excluded because the pulsation period of the G-type main-sequence stars is shorter than a few hours[13]. The possibility of the brightness variation being due to rotation must be carefully distinguished from its being due to orbital motion, on the basis of the difference in the shape of the light curves. The variability type of KIC 9459362 and KIC 6034120 is classified as stellar rotational modulation[14]. The energy of superflares can be explained by the magnetic energy stored near starspots. If the time variations in the brightnesses of KIC 9459362 and KIC 6034120 are caused by their rotation and the existence of starspots, their brightness variations suggest that solar-type stars with superflares have much larger starspots than does the Sun (for more details on the relation between starspots and superflares, see Supplementary Information). Typical periods of brightness variation range from one day to a few tens of days. According to the results of the variability-type classification[14], about 65% of the brightness variations in the quarter-1 data can be taken to result from stellar rotational modulation. Although we could not exclude the possibility of the binary-eclipse scenario by using only photometric data, we assumed that the period of quasi-periodic modulation corresponds to the period of stellar rotation (for more details on the possibility of superflares on secondary stars, see Supplementary Information).

The average occurrence frequency of superflares can be estimated from the number of observed superflares, the number of observed stars and the length of the observation period. For example, in the case of slowly rotating G-type main-sequence stars with surface temperatures of 5,600 K $\leq T_{\mathrm{eff}} <$ 6,000 K, 14 superflares were detected from the data on about 14,000 stars over 120 d. Hence, the occurrence frequency of superflares is 2.9×10^{-3} flares per year per star, which corresponds to a superflare occurring on a star once every 350 yr. The occurrence frequency distribution of superflares on solar-type stars can be fitted in the energy range $\geq 4 \times 10^{34}$ erg using a simple power law (Fig. 2a, b). The frequency distribution function of superflares on solar-type stars is similar to those of solar flares[15] and stellar flares on red dwarfs[16]. The power-law index of the distribution of superflares (-2.0 to -2.3) is nearly equal to that of the distribution of solar flares. The occurrence frequency of superflares on slowly rotating G-type main-sequence stars is about ten times lower than the average occurrence frequency (Fig. 2b). The occurrence frequency also depends on the surface temperature of the star (Fig. 2c, d), and is higher for lower-temperature (5,100 K $\leq T_{\mathrm{eff}} <$ 5,600 K) G-type main-sequence stars than for higher-temperature (5,600 K $\leq T_{\mathrm{eff}} <$ 6,000 K) stars. The superflares of 10^{34} erg on Sun-like stars (that is, slowly rotating G-type main-sequence stars with surface temperatures of 5,600 K $\leq T_{\mathrm{eff}} <$ 6,000 K; Fig. 2d) occur once every 800 yr, and those of 10^{35} erg occur once every

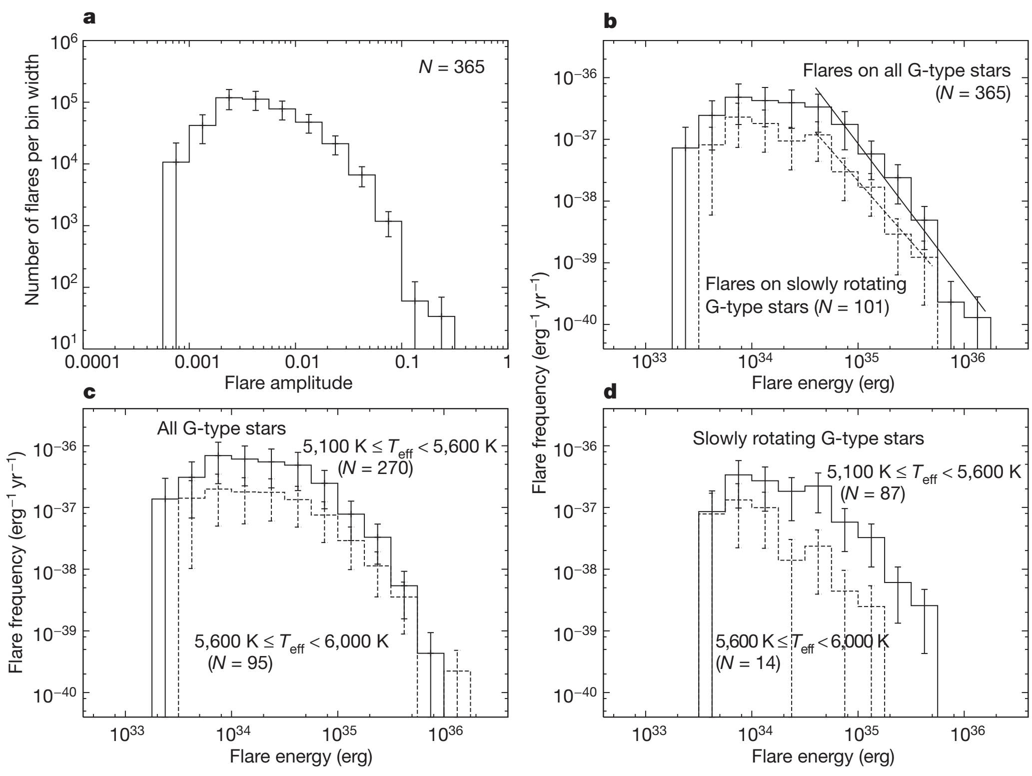

Figure 2 | Frequency distribution of superflares on G-type main-sequence stars. **a**, Number distribution of flares as a function of observed flare amplitude. The errors were estimated from the 10% uncertainty in the amplitude and the square root of the event number in each bin. The number of flares (N) is 365. **b**, Frequency distribution of flares as a function of flare energy. The vertical axis indicates the number of superflares per star per year per unit energy. The histograms show the frequency distribution of flares on all G-type main-sequence stars (solid line) and on G-type main-sequence stars excluding the stars that have quasi-periodic brightness modulations with periods shorter than 10 d (dashed line). The error bars represent the 1σ uncertainty in the frequency estimated from the uncertainty in the energy estimation and the square root of the event number. The occurrence distribution of superflares can be fitted by a simple power-law function in the large-energy regime between 4×10^{34} and 2×10^{36} erg. The power-law indexes of the distributions are -2.3 ± 0.3 and -2.0 ± 0.2, respectively (downward-sloping lines). Because the detection completeness of flares with energy less than 4×10^{34} erg is low (10^{-3} for 10^{33} erg and 10^{-1} for 10^{34} erg), we did not use these data for the fitting. Because of the small number of events in the energy bins above 10^{36} erg, the fit does not well represent the data. **c**, Same as **b**, but for flares on all lower-temperature (5,100 K $\leq T_{\mathrm{eff}} <$ 5,600 K; solid line) stars and all higher-temperature (5,600 K $\leq T_{\mathrm{eff}} <$ 6,000 K; dashed line) stars. **d**, Same as **c**, but only for flares on slowly rotating stars (that is, excluding stars showing brightness variations with periods shorter than 10 d).

5,000 yr, although accurate statistics are difficult to obtain because only 14 superflares have been observed on Sun-like stars.

As shown in Fig. 3a, the maximum energy of a superflare does not show any clear correlation with the period of stellar rotation, assuming that the period of brightness modulation corresponds to the rotational period of the star. If the flare energy can be explained by the magnetic energy stored near the starspot[11], this result suggests that the maximum magnetic energy stored near the spot does not have a strong dependence on the period of rotation. This result also implies that superflares can occur on slowly rotating solar-type stars like the Sun.

The frequency of superflares tends to decrease as the period increases to periods longer than a few days (Fig. 3b). The frequency of superflares on the slowly rotating stars (rotational period, >10 d) is only 1/20 of that of superflares on rapidly rotating stars. The rotation period correlates with the chromospheric activity, which is known to be an indicator of the magnetic activity of the stars[17], and the more rapidly rotating stars have higher magnetic activity[18]. According to the dynamo theory of magnetic field generation, magnetic activity results from the interaction between rotation and convection[19], and the rapid rotation can cause the high magnetic activity. Our result implies that rapidly rotating stars with higher magnetic activity can cause more frequent superflares. The frequency distribution of superflares saturates for periods of less than a few days. A similar saturation is known for the relationship between the coronal X-ray activity and the rotation period[20].

The rotation period of a star is also known to be related to the star's age, with younger stars rotating more rapidly[21,22]. Our findings suggest that superflares occur more frequently on the solar-type stars younger than the Sun. Moreover, on solar-type stars similar in age to the Sun, superflares occur less frequently but are nearly equal in energy to the superflares on the younger stars.

It has been pointed out that there is no record of solar superflares over the past 2,000 yr (ref. 3). According to the measurement of the impulsive nitrate events in polar ice, the largest proton flare event during the past 450 yr is the Carrington event[23], which occurred on 1 September 1859[24]. The total energy released in this flare was estimated to be of order 10^{32} erg (ref. 25), which is only 1/1,000 of the maximum energy of flares on slowly rotating Sun-like stars. It has also been proposed that hot Jupiters have an important effect on stellar magnetic activity[7,26,27] and that superflares occur only on solar-type stars with hot Jupiters. However, there is no hot Jupiter in the Solar System. For these reasons, it was suggested that a superflare on the Sun is extremely unlikely[3,7]. Although the Kepler mission has discovered 1,235 exoplanet candidates around 997 host stars from a survey of 156,453 stars[28], no exoplanet has been found around the 148 G-type main-sequence stars with superflares. For a solar-type star with a hot Jupiter, the probability of a transit of the planet across the star is about 10% averaged over all possible orbital inclinations. If the superflares on all 148 stars were caused by hot Jupiters, then Kepler should detect 15 of them from transits. However, the Kepler planetary-transit search is almost complete for hot Jupiters[29], and the non-detection of planetary transits therefore suggests that hot Jupiters associated with superflares are rare.

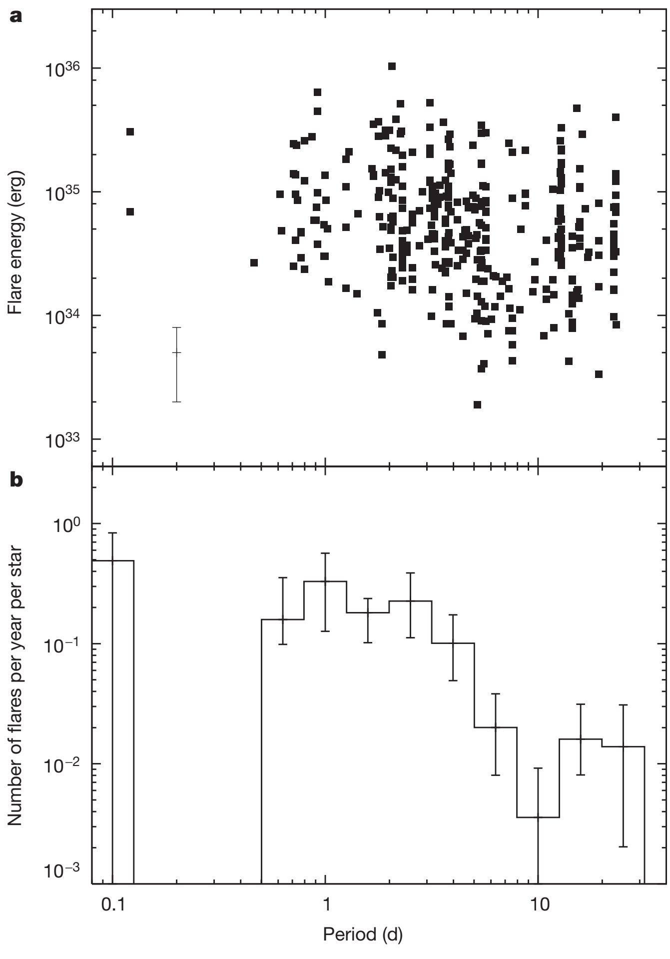

Figure 3 | Relations between the brightness variation period and the properties of flares on G-type main-sequence stars. **a**, Scatter plot of the flare energy as a function of the variation period. An apparent negative correlation between the variation period and the lower limit of the flare energy is caused by the detection limit of our flare-search method. The vertical bar in the panel indicates the typical uncertainty in the flare energy. **b**, Distribution of the occurrence of flares in each period bin as a function of variation period. The vertical axis indicates the number of flares with energy $\geq 5 \times 10^{34}$ erg per star per year. The error bars represents the 1σ uncertainty estimated from the uncertainty in the energy estimation and the square root of the event number in each period bin.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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