

Starspot Activity and Superflares on Solar-type Stars

Hiroyuki Maehara

email: h.maehara@oao.nao.ac.jp

Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, 3037-5
Honjo, Kamogata, Asakuchi, Okayama, Japan, 719-0232

Abstract. Recent high-precision photometry from space (e.g., Kepler) enables us to investigate the nature of “superflares” on solar-type stars. The bolometric energy of superflares detected by Kepler ranges from 10^{33} erg to 10^{36} erg which is 10-10,000 times larger than that released by a typical X10 class solar flare. The occurrence frequency (dN/dE) of superflares as a function of flare energy (E) shows the power-law distribution with the power-law index of ~ -1.8 for $10^{34} < E < 10^{36}$ erg. Most of superflare stars show quasi-periodic light variations which suggest the presence of large starspots. The bolometric energy released by flares is consistent with the magnetic energy stored near the starspots. The occurrence frequency of superflares increases as the rotation period decreases. However, the energy of the largest flares observed in a given period bin does not show any clear correlation with the rotation period. These results suggest that superflares would occur on the slowly-rotating stars.

Keywords. stars:activity, stars:flare, stars:solar-type

1. Introduction

Solar flares are sudden and rapid releases of magnetic energy stored near the sunspots caused by the magnetic reconnection (e.g., Shibata & Magara 2011). The typical solar flare releases the order of $10^{29} - 10^{32}$ erg of energy with the time scale of minutes to hours. The occurrence frequency of solar-flares (dN/dE) as a function of flare energy (E) can be well represented by a power-law function ($dN/dE \propto E^{-\alpha}$) with the power-law index of $\alpha = 1.5 - 1.9$ in the wide energy range from 10^{24} erg to 10^{32} erg (e.g., Crosby *et al.* 1993, Shimizu 1995, Aschwanden *et al.* 2000). The energy of the largest solar flares observed so far is the order of 10^{32} erg (e.g., Emslie *et al.* 2012) and such solar flares occur approximately once in 10 years. It is unclear that whether more energetic solar flares would occur on our Sun because the history of the modern solar flare research is less than 100 years.

More energetic flares, called “superflares”, have been observed on solar-type stars other than the Sun (e.g., Weaver & Naftilan 1973, Landini *et al.* 1986, Schaefer 1989, Schaefer *et al.* 2000). Recent space-based, high-precision photometry of large number of stars by the Kepler space telescope discovered many superflares on solar-type stars (G-type main sequence stars; e.g., Maehara *et al.* 2012, Shibayama *et al.* 2013). The bolometric energy released by the superflares observed with the Kepler ranges from 10^{33} to 10^{36} erg, which is $10 - 10^4$ times more energetic than that of the largest solar flares observed so far ($\sim 10^{32}$ erg).

2. Data set of superflares on solar-type stars

Maehara *et al.* (2012) and Shibayama *et al.* (2013) searched for superflares on solar-type stars from the long-cadence (~ 30 min interval) data observed with the Kepler

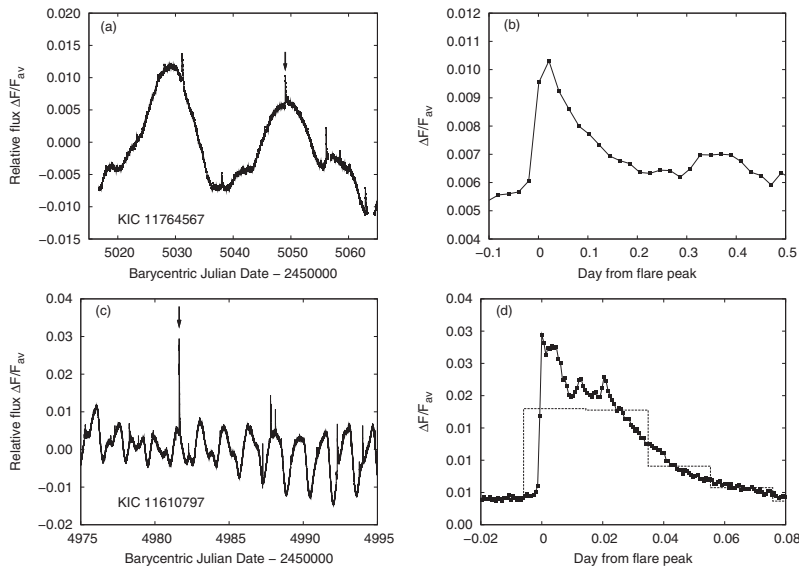


Figure 1. (a): Long-term light variations of the G-dwarf KIC 11764567 from the long-cadence data. The vertical axis means the relative difference between observed brightness of the star and the average brightness during the observation period. The horizontal axis means the times of the observations in Barycentric Julian Date. (b): Enlarged light curve of a superflare on KIC 11764567 indicated by the down arrow in panel (a) from the long-cadence data. (c): Same as (a), but for KIC 11610797 from the short-cadence data. KIC 11610797 from the short-cadence data (c). (d): Same as (c), but for a superflare on KIC 11610797 indicated by the down arrow in panel (c). Filled-squares with solid-lines and dashed-lines represent the light curves from short- and long-cadence data, respectively.

space telescope from 2009 April (quarter 0: Q0) to 2010 September (Q6). The number of superflares detected in Shibayama *et al.* (2013) is 1547 on 279 stars. Maehara *et al.* (2015) searched for superflares from short-cadence (~ 1 min interval) data observed between 2009 April (Q0) and 2013 May (Q17) and found 187 superflares on 23 stars.

3. Statistical properties of superflares

3.1. Light curves of superflares on solar-type stars

The light curves of typical superflares on solar-type stars are presented in figure 1. As shown figure 1 (a) and (c), most of the stars with superflares show the quasi-periodic brightness modulations with the period and amplitude of $\sim 0.5 - \sim 30$ days, and $\sim 0.1 - \sim 5$ %, respectively. These light variations can be explained by the rotation of the star with spotted surface (e.g., Notsu *et al.* 2013). Figure 1 (b) and (d) show the enlarged light curve of a “spike” (as indicated by a down arrow in figure 1 (a) and (c)) which are thought to be a “superflare”. The normalized amplitude of the detected superflares ranges from $\sim 10^{-3}$ to $\sim 8 \times 10^{-2}$. The flare light curves from short-cadence (e.g., 1 (d)) show that some of energetic superflares exhibit flare oscillations with the peak separation of the order of 100-1000 seconds during the decay phase. The duration of typical superflares detected from long-cadence data is ~ 0.1 day and the duration of superflares from short-cadence data ranges from a few minutes to ~ 100 minutes. The bolometric energy of superflares detected from the long-cadence data ranges from the order of 10^{33} to 10^{36} erg.

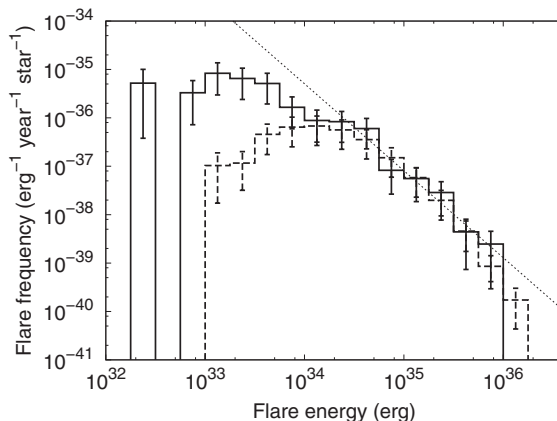


Figure 2. Bold solid and dashed lines represent the occurrence frequency of superflares on all solar-type stars from short- (Maehara *et al.* 2015) and long-cadence data (Shibayama *et al.* 2013) as a function of the bolometric energy of superflares. The vertical axis indicates the number of observed superflares per star, per year, and per unit energy. The thin-dotted line indicates the power-law fit to the frequency distribution in the energy range between 10^{34} and 3×10^{36} erg. The power-law index is -1.8 ± 0.2 .

3.2. Occurrence frequency of superflares

Figure 2 shows the occurrence frequency distribution of superflares on solar-type stars as a function of flare energy. As mentioned in Maehara *et al.* (2012), Shibayama *et al.* (2013), and Maehara *et al.* (2015), the frequency-energy distribution of superflares on solar-type stars can be represented by a power-law function in the large energy regime ($E_{\text{flare}} > 10^{34}$ erg). The power-law index of frequency distribution is -1.8 ± 0.2 . This value is consistent with the power-law indexes of frequency distributions of solar-flares (e.g., Aschwanden *et al.* 2000) and stellar flares on M-dwarfs (e.g., Shakhovskaia 1989).

Shibata *et al.* (2013) found that the frequency-energy distribution of superflares on solar-type stars and that of solar-flares are roughly on the same power-law line. Figure 3 shows the comparison between the frequency-energy distribution of superflares on solar-type stars and those of solar-flares, micro-flares, and nano-flares. All of them are roughly on the same power-law line with the power-law index of -1.8 (thin-solid line in figure 3).

The frequency of superflares depends on the rotation period and effective temperature (e.g., Maehara *et al.* 2012, Notsu *et al.* 2013, Candelaresi *et al.* 2014). As shown in figure 4, the frequency of superflares decreases as the rotation period increases in the long-period regime ($P_{\text{rot}} > 3$ days). On the other hand, in the short-period regime ($P_{\text{rot}} < 3$ days), the frequency is roughly constant. The similar “saturation” of the energy release rate by flares in the short-period (small Rossby number) regime was reported by Davenport (2016).

3.3. Bolometric energy of superflares

Solar and stellar flares are thought to be rapid releases of magnetic energy stored near sunspots and starspots. Therefore the total energy released by solar and stellar flares (E_{flare}) must be limited by the magnetic energy (E_{mag}). According to Shibata *et al.* (2013), the flare energy can be written as

$$E_{\text{flare}} \approx f E_{\text{mag}} \approx f \frac{B^2 L^3}{8\pi} \approx f \frac{B^2 A_{\text{spot}}^{3/2}}{8\pi}, \quad (3.1)$$

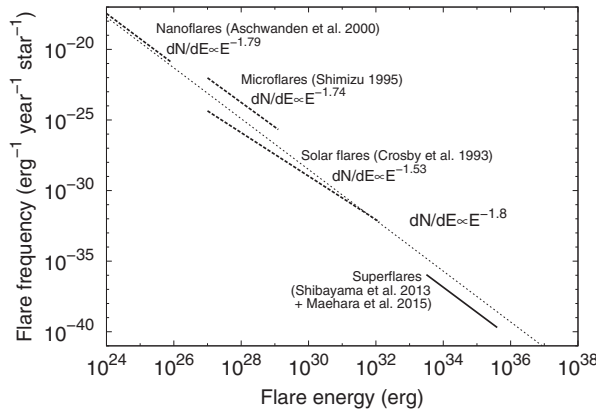


Figure 3. Comparison between the energy-frequency distribution of superflares on Sun-like stars and those of solar flares. Bold-solid line represents the power-law frequency distribution of superflares on Sun-like stars (early G-dwarfs with $P_{\text{rot}} > 10$ days) taken from Shibayama *et al.* (2013) and Maehara *et al.* (2015). Bold-dashed lines indicate the power-law frequency distribution of solar flares observed in hard X-ray (Crosby *et al.* 1993), soft X-ray microflares (Shimizu 1995), and EUV nanoflaers (Aschwanden *et al.* 2000). Occurrence frequency distribution of superflares on Sun-like stars and those of solar flares are roughly on the same power-law line with an index of -1.8 (thin-solid line; Shibata *et al.* 2013).

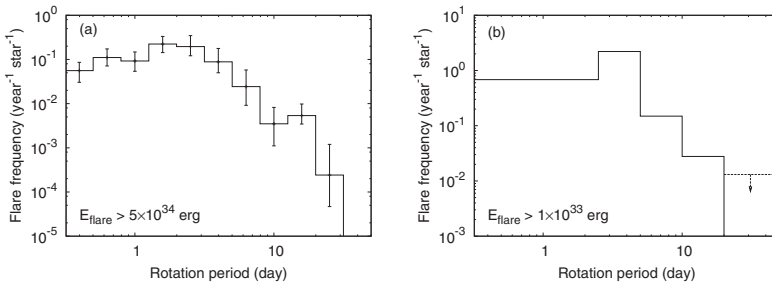


Figure 4. (a): Frequency of the superflares with $E_{\text{flare}} > 5 \times 10^{34}$ erg as a function of the rotation period derived from the long-cadence data (Notsu *et al.* 2013). (b): Same as (a), but for the superflares with $E_{\text{flare}} > 1 \times 10^{33}$ erg derived from the short-cadence data (Maehara *et al.* 2015) The dashed line and down-arrow indicate the upper limit of the flare frequency in the period bin ($1/80 \text{ year}^{-1}$).

where f is the fraction of magnetic energy released by a flare, B , L , and A_{spot} are the magnetic field strength, the scale length of active region, and the area of sunspots/starspots. According to Aschwanden *et al.* (2014), $f < 0.1$. The equation 3.1 suggests that the upper limit of energy released by flares is proportional to $A_{\text{spot}}^{3/2}$. Figure 5 shows the scatter plot of the energy of superflares and solar flares as a function of the area of sunspots / starspots. The area of starspots on superflare stars was estimated from the amplitude of rotational brightness variations. Solid line in figure 5 indicates the analytic relation between flare energy and spot area based on the equation 3.1 for $f = 0.1$ and $B = 3000$ G. Majority of superflares and almost all of solar flares are below the analytic line. This result suggests that the energy released by a flare is basically consistent with the magnetic energy stored near sunspots / starspots and the large starspots whose area is larger than $\sim 1\%$ of the area of solar hemisphere are required to produce superflares with $E_{\text{flare}} > 10^{34}$ erg.

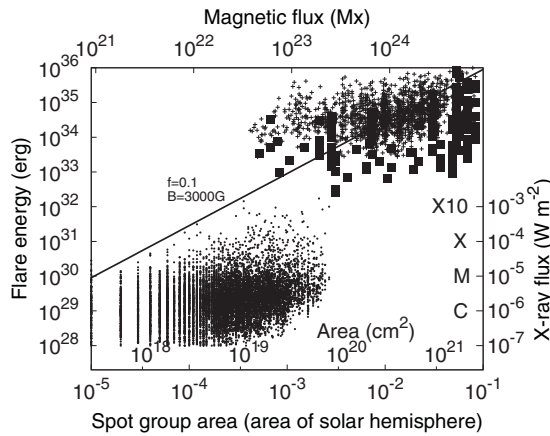


Figure 5. Scatter plot of flare energy as a function of the area of starspots from Maehara *et al.* (2015). The lower horizontal axis indicates the area of starspot group in the unit of the area of solar hemisphere ($3 \times 10^{22} \text{ cm}^2$). The upper horizontal axis indicates the magnetic flux if we assume that the magnetic field strength around spots (B) is 3000 G. The vertical axis represents the energy released by each flare. Filled-squares and small-crosses indicate superflares on solar-type stars from the short- and long-cadence data, respectively. Small filled-circles represent solar flares based on the data retrieved from the website of the National Geophysical Data Center of the National Oceanic and Atmospheric Administration (NOAA/NGDC), Solar-Terrestrial Physics Division at <http://www.ngdc.noaa.gov/stp/> (Ishii *et al.*, private communication).

However, some superflares occurred on the stars with small amplitude light variations (superflares located above the analytic line in figure 5). The energy released by such superflares is larger than that estimated from equation (3.1). Notsu *et al.* (2015) measured the rotational velocity ($v \sin i$) of superflare stars by high-dispersion spectroscopy and found that the superflares occurred on the stars with low inclination angle (i) are located above the analytic line. In the case of the star with low inclination angle, the amplitude of rotational brightness modulations caused by starspots becomes smaller than that expected from the area of starspots.

Figure 6 shows the scatter plot of flare energy as a function of the rotation period based on the data set of superflares taken from Shibayama *et al.* (2013) and Maehara *et al.* (2015). Maehara *et al.* (2012) and Notsu *et al.* (2013) pointed out that the energy of the largest superflares observed in a given period bin does not depend on the rotation period. This result indicates that superflares can occur on not only the rapidly-rotating stars but also slowly-rotating stars. As shown in figure 4, the frequency of superflares decreases as the rotation period increases in the period range of $P_{\text{rot}} > 3$ days. On the other hand, the energy of the largest superflares depends on the area of starspots (figure 5) and does not depend on the rotation period. These results imply that the appearance frequency of large starspots which could produce superflares may decrease as the rotation period increases.

3.4. Decay timescale of superflares vs. flare energy

Maehara *et al.* (2015) found a clear correlation between the duration of superflares and the energy of superflares. Figure 7 shows the scatter plot of the flare duration (e -folding time) as a function of the bolometric energy of superflares. A linear fit for the duration (τ) and energy (E_{flare}) of superflares on the log-log plot yields the following correlation:

$$\tau \propto E_{\text{flare}}^{0.39 \pm 0.03}. \quad (3.2)$$

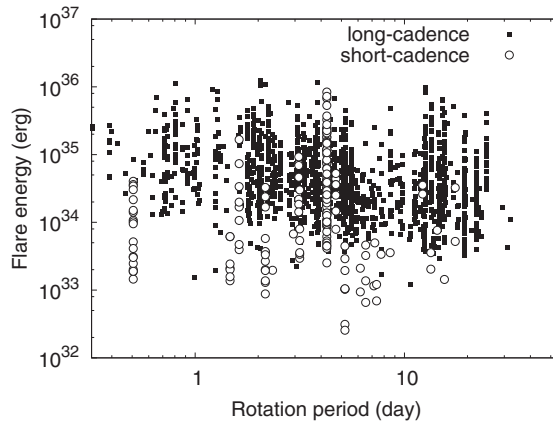


Figure 6. Scatter plot of flare energy as a function of the rotation period. The horizontal and vertical axis indicate the rotation period of superflare stars and the bolometric energy of superflares. Filled squares and open circles represent each superflares detected from the long-cadence data (taken from Shibayama *et al.* 2013) and short-cadence data (from Maehara *et al.* 2015), respectively.

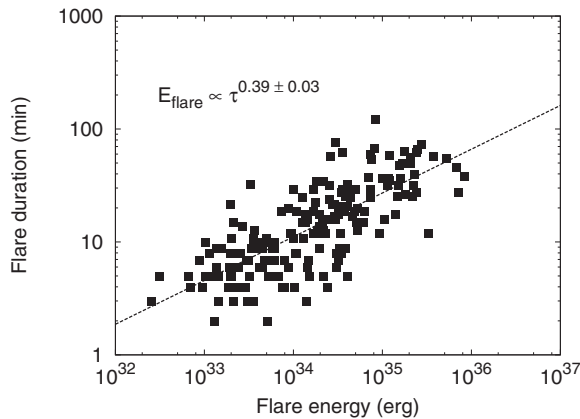


Figure 7. Scatter plot of the flare duration (*e*-folding time) as a function of flare energy. Filled squares indicate superflares on solar-type stars from short-cadence data (taken from Maehara *et al.* 2015). Dotted line represents the linear regression to the data set of superflares. The power-law slope of the line is 0.39 ± 0.03 .

Veronig *et al.* (2002) found a similar correlation between the decay time and X-ray fluence of solar flares observed with GOES which shows the power-law slope of $\sim 1/3$. Moreover, Christie *et al.* (2008) reported that the correlation between the duration and peak flux of solar flares observed with RESSI also shows similar power-law slope of ~ 0.2

As discussed in the previous subsection, the flare energy is a part of magnetic energy stored near the starspots. From equation (3.1), if the magnetic field strength of starspots (*B*) is almost the same on all the solar-type stars, the flare energy would be proportional to L^3 ,

$$E_{\text{flare}} \propto L^3, \tag{3.3}$$

where *L* is the scale length of the active region. On the other hand, the duration of white-light flares is roughly comparable to the reconnection time (τ_{rec}) that can be written as

Table 1. Comparison between the fraction of planet-hosting stars among all solar-type stars and that among superflare stars.

	Number of planet-hosting stars ¹	Total number of stars	Fraction
All solar-type stars	1029	102251	~1.0 %
Superflare stars	1	279	~0.4 %

Note:

¹ The data set of exoplanets were retrieved from the NASA Exoplanet Archive (<http://exoplanetarchive.ipac.caltech.edu/>) on Dec 14th, 2016.

follows by using the Alfvén time ($\tau_A = L/v_A$):

$$\tau_{\text{flare}} \sim \tau_{\text{rec}} \sim \tau_A/M_A \sim L/v_A/M_A, \quad (3.4)$$

where v_A is the Alfvén velocity, and M_A is the non-dimensional reconnection rate (0.1–0.01 for the fast reconnection; Shibata & Magara 2011). From equation (3.3) and (3.4), if we assume that v_A is roughly the same on all the solar-type stars, the duration of flares can be written as

$$\tau_{\text{flare}} \propto E_{\text{flare}}^{1/3}. \quad (3.5)$$

The power-law slope for the correlation between the flare duration and flare energy derived from the reconnection model ($\sim 1/3$) is comparable to the observed value of 0.39 ± 0.03 .

3.5. Superflares and close-in planet

It has been discussed that close-in giant planets such as hot Jupiters can affect the stellar magnetic activity (e.g., Cuntz *et al.* 2000, Ip *et al.* 2004). Rubenstein & Schaefer (2000) proposed that superflares are caused by the magnetic reconnection between magnetic fields of the primary star and a close-in Jovian planet, and the superflares on solar-type stars occur only on the stars with hot Jupiters on the basis of an analogy with the RS CVn binaries. However, Maehara *et al.* (2012) found no hot Jupiters orbiting around 148 solar-type stars showing superflares. Table 1 shows the comparison between the fraction of planet hosting stars among all solar-type stars in the Kepler field and that among superflare stars. Only 1 confirmed exoplanet (Kepler-491 b) was discovered around 279 superflare stars listed in Shibayama *et al.* (2013). The fraction of planet-hosting stars is not significantly different between in all solar-type stars and superflare stars. This result suggests that hot Jupiters are not necessary to produce superflares on solar-type stars.

4. Summary

Statistical studies of superflares on solar-type stars by using the Kepler data reveal the following results:

- The frequency-energy distribution of superflares on solar-type stars can be represented by a power-law function with the power-law index of ~ -1.8 . The frequency distribution of superflares on solar-type stars and those of solar flares are almost on the same power-law line.
- The average frequency of superflares depends on the rotation period (P_{rot}). In the short-period regime ($P_{\text{rot}} < 3$ days), the flare frequency is almost constant. On the other hand, in the long-period regime, ($P_{\text{rot}} > 3$ days), the flare frequency decreases as the rotation period increases.
- The upper limit of flare energy depends on the area of starspots. The relation between the flare energy and the area of starspots (A_{spot}) suggests that the largest flare

energy is proportional to $A_{\text{spot}}^{3/2}$. However, there is no clear correlation between the energy of largest flares observed in a given period bin and the rotation period. These results indicate that slowly-rotating solar-type stars can produce superflares if they have large starspots.

- The flare duration (τ_{flare}) increases as the the energy of flares (E_{flare}) increases. The data set of superflares from the short-cadence data yields the following correlation:

$$\tau_{\text{flare}} \propto E_{\text{flare}}^{0.39 \pm 0.03}.$$

This suggests that the time-scale of flares is determined by the Alfvén time.

- There is no significant difference between the fraction of planet-hosting stars among all solar-type stars in the Kepler field and that among superflare stars. Hot Jupiters may not be necessary to produce superflares on solar-type stars.

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