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Chapter 3: Advances in observations of stellar flares

Solar and Stellar Flares and their Effects on Planets
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Discovery of Superflares

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Abstract. We have discovered 1547 'superflares' on about 279 G-type main-sequence stars by using the Kepler-spacecraft data of Q0-Q6. 'Superflares' mean flares that radiate total energy 10 times or more larger than that of the largest flare in the Sun ever recorded. We here briefly review our current understandings on superflares and superflare stars obtained by analyzing the Kepler data and follow-up high dispersion spectra.

Keywords. stars:activity, stars:flares, stars:Solar-type

1. Introduction

Solar flares are most energetic eruptive events on the surface of of the Sun, and they are thought to be caused by impulsive release of the magnetic energy stored around spots (for a review, see e.g. Shibata & Magara 2011). They are observed in all the wavelengths from radio through γ-rays. The timescale is minutes to hours, and the total radiated energy in one event reaches 10^{32} ergs.

The occurrence frequency (dN/dE) of the solar flare is well expressed as a power-law function of the total flare energy (E),

$$\frac{dN}{dE} \propto E^{-\alpha}, \tag{1}$$

with α=1.5-1.9 in the energy range of 10^{24} to 10^{32} erg (e.g. Cosby *et al.* 1993; Shimizu 1995; Aschwanden *et al.* 2000). Carrington (1859) recorded a solar flare in 1958 for the first time in the history of the human beings. The total energy of this "Carrington flare" is estimated to be of the order of 10^{32} erg on the basis of a sketch of the white light flare by Tsurutani *et al.* (2003). This flare is still regarded as one of the largest solar flares, and the Carrington-class flare is supposed to occur once in several tens of years. This is naturally explained by that statistics on the solar flare are based on the results of the solar physics by the modern research methods for these ~100 years at most.

Can the Sun show more energetic flares? This is the essential motivation of our research on "superflares" that have an energy of 10^{33} erg, or more, i.e. 10 times, or more energetic than the largest solar flares observed so far.

Coronal mass ejections (CMEs) sometimes accompany solar flares. Some of them hit the magnetosphere of the Earth, and such Earth-directed CMEs may cause geomagnetic storms. Geomagnetically induced currents then arise in long electrical conductors, and can cause damage to our lives by, for example, destruction of electrical equipment and communication network. In fact, about 6 million people in Quebec, Canada suffered an electrical power blackout for 9 hours caused by a huge geomagnetic storm which originated in a solar flare on 1989 March 9th (Allen *et al.* 1989). The Carrington event caused the largest geomagnetic storm in the past 200 years (Tsurutani *et al.* 2003), and a failure of telegraph systems in Europe and North America happened with this storm

(Loomis 1861). If a superflare would occur on the Sun, we might confront disaster†. Research on superflares would have an impact on solar and stellar astrophysics, as well as the science of disaster prevention.

It is impossible, however, to give an answer to the question "Can the Sun cause superflares?" by observations of the Sun for a realistic timescale, say, several years. In contrast, it may be possible to give an answer *statistically* by several years observations of many G-type main sequence stars, in other words, solar-type stars.

A various kinds of stars show flares similar to those of the Sun (for a review, Gershberg 2005). The flare energy, especially in young stars including T Tau-type stars, and binary stars like RS CVn-type binaries, sometimes exceeds 10^{33} erg, and reaches 10^{38} erg (Shibata & Yokoyama 2002, and references therein). Concerning solar-type stars, an only limited number of such energetic flares have been discovered (Landini *et al.* 1986; Schaefer 1989; Schaefer *et al.* 2000, and references therein). The number is furthermore reduced by choosing superflares only on slowly rotating solar-type stars like the Sun‡, and is far from being enough to do statistical research on superflares. The difficulty in detecting superflares on solar-type stars is due to an extremely low flare frequency and small amplitude in the continuum. The total solar irradiance increased only 0.027 % during one of the largest solar flares on the Sun that occurred on 2003 October 28th (X17 class) (Kopp *et al.* 2005). This fact suggests that the optical continuum increases by only about 1 % even at the maximum of a 10^{34}-erg superflare that is 100 times more energetic than largest solar flares.

2. Discovery of many superflares from Kepler data

NASA's Kepler mission brought a revolution in this situation (Borucki *et al.* 2010; Koch *et al.* 2010). Extrasolar planet search by detection of planetary transit is the primary purpose of this mission. The high-precision photometry by the Kepler spacecraft enabled us to detect transits of Earth-like planets with an amplitude smaller than 0.01%, and superflares on solar-type stars also. The Kepler spacecraft has a 0.95 m effective aperture Schmidt telescope monitoring about 160,000 stars in a fixed field between Lyrae and Cygni. Photometric data were recorded with about 30 minutes cadence for almost all stars, and about 1 minute cadence for some selected stars. About 80,000 stars among them are Solar-type stars. The Kepler data are open to public at the web site of the Mikulski Archive for Space Telescopes (MAST)¶.

Maehara *et al.* (2012) found 365 superflares on 148 solar-type stars by investigating the long cadence data obtained with the Kepler spacecraft for the first ∼120 days of the mission (Q0-Q1). By extending the data up to the first ∼500 days (Q0-Q6), 1,547 superflares on 279 stars were detected in total (Shibayama *et al.* 2013).

Examples of the superflare is shown in figure 1. These stars increased the continuum flux by about 1.4 %, and more than 8 % at the maxima of these flares, and the total radiated energy of each flare was estimated to be 5.6×10^{34} erg and 3.0×10^{35} erg, respectively (Maehara *et al.* 2012). Slow modulations of the flux, other than superflares, are regarded as being due to rotation of the star having big star spots (Notsu *et al.* 2013b). The rotation period ($P_{\rm rot}$), thus, can be measured by a period analysis of the light curve.

Figure 2 displays two examples of long term light curve of superflare stars. KIC 10422252

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† see e.g. http://science.nasa.gov/science-news/science-at-nasa/2008/06may_carringtonflare/

‡ See also discussion by Nogami *et al.* (2014) on the data quality in Schaefer *et al.* (2000)

¶ http://archive.stsci.edu/kepler/

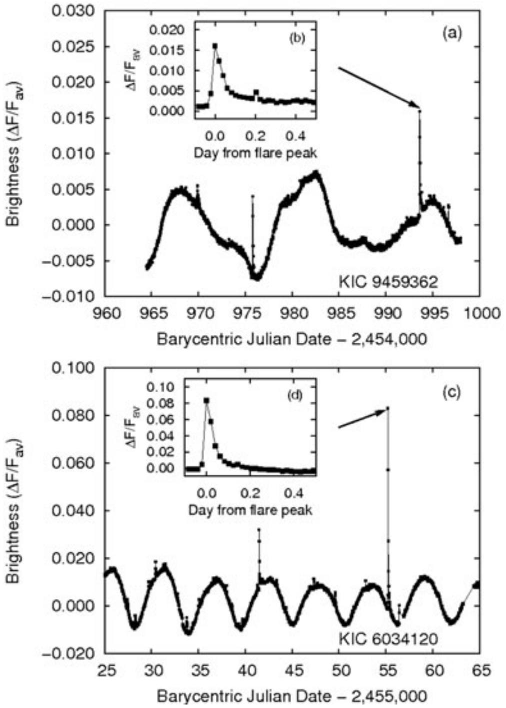

Figure 1. Examples of superflares on solar type stars KIC 9459362 (upper panel (a)) and KIC 6034120 (lower panel (b)). The superflares indicated by the arrows are enlarged in the inserted small panels. This figure is the same as figure 1 in Maehara *et al.* (2012).

is the most active star in our samples, and exhibited 57 superflares in about 500 days. The main period of the brightness variation is estimated to be 5.2 days, but we can see beat phenomena. Frasca *et al.* (2010) suggested that starspot systems with differential rotation show such a light curve. KIC 10471412 in the lower panel is an analog of the Sun in terms of the surface temperature, and surface gravity. The rotation period of this star is estimated to be 15.1 days (Shibayama *et al.* 2013), slightly shorter than that of the Sun, but this star is, obviously, not young. Superflare can occur even on such systems.

The flare frequency over the flare energy is shown in figure 3. The occurrence frequency of superflares on all solar-type stars is expressed by a power law of the flare energy (equation 1) with $\alpha \simeq 2.2$ (figure 3; Shibayama *et al.* 2013), though the power index is a little larger than that in the case of the Sun. When selecting flares on slowly rotating solar-type star ($P_{\rm rot} \geqslant 10$ days) like the Sun, equation 1 still holds with $\alpha \simeq 2.0$, although the absolute value of the flare frequency becomes a little smaller. The flare frequency seems saturated with the flare energy smaller than $10^{34.5}$ ergs. This is because the completeness of superflare detection decreases below this energy. Short cadence data is more suitable for detection of small energy flares than long cadence data. Analyses of the short cadence data by Maehara *et al.* (2015) showed that the power law distribution of the flare frequency is extended up to $E \sim 10^{33}$ ergs, and that this distribution is in good accordance with that of the solar flare (see also Maehara *et al.* 2016).

Notsu *et al.* (2013b) showed that the flare frequency increases with shorter rotation periods (cf. the right panel of figure 3), but it is saturated at $P_{\rm rot} <$ a few days. A similar relationship between the coronal X-ray activity and rotation period is known (Randich 2000). Interestingly, the maximum energy of the superflare is about 10^{36} ergs,

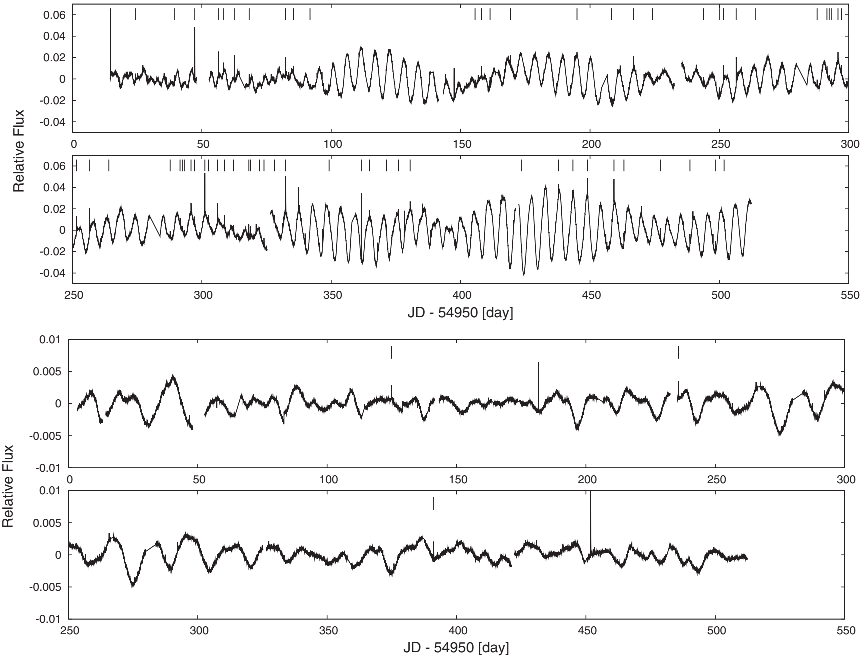

Figure 2. Examples of long term light curve of superflare stars. KIC 10422252, the most active star in our samples exhibited 57 superflares in about 500 days (upper panel). A period analysis yields 5.2 days as the best estimated period, but the amplitude modulation implies a beat phenomenon between brightness variations with close periods. KIC 10471412 which caused 4 superflares (lower panel) is similar to the Sun in terms of the surface temperature, and surface gravity. Although the rotational period is estimated to be 15.1 days, slightly shorter than that of the Sun, this star is obviously not young. This figure is taken from Shibayama *et al.* (2013).

independent of the rotation period, though it may decrease with an increase of P_{rot} over 10 days. Shibayama *et al.* (2013) and Maehara *et al.* (2015) made clear that the flare energy has a good relation with the spot group area through the wide range from solar flares to superflares. These facts indicate that it is more difficult for longer P_{rot} stars to generate large spots but the flare energy does not depend on P_{rot} once large spots are generated.

3. High dispersion spectroscopy of superflare stars

The discoveries of superflares and subsequent analyses of the Kepler data, as described in the previous section, suggests that the Sun can cause superflares radiating even 1,000 times more energy than that of the largest solar flares so far recorded. However, we have to clarify the following matters: Are these superflare stars single or binary? Does the period of the brightness variation really represent the rotation period? And, does the superflare star really have gigantic spots?

We then started a project of optical high dispersion spectroscopy of superflare stars with the SUBARU telescope and High Dispersion Spectrograph (HDS). Fifty superflare stars have been observed so far, and we do not find evidence of binarity in 34 stars among them (Notsu *et al.* 2015a, b; see also Notsu *et al.* 2016). Note that this judgment is based on that absorption lines in a spectra or at most a few for each star do not have

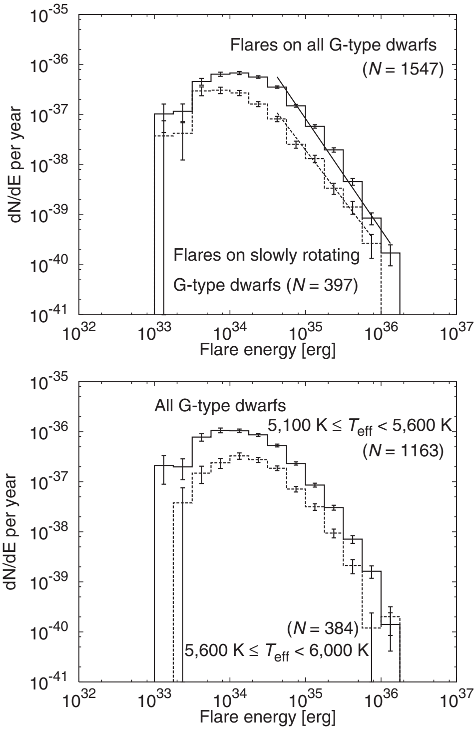

Figure 3. Flare frequency vs flare energy diagrams on the basis of the data in Shibayama *et al.* (2013). In the left panel, the solid line represents the flare frequency of all G-type main sequence stars (solar-type stars), and the dashed line represents that of slowly rotating solar-type stars ($P_{\rm rot} > 10$ days). The flare frequency becomes lower if only slowly rotating stars are selected. The flare frequency distribution is, however, well expressed with power laws of the flare energy having similar power indices of about 2.0. The right panel shows the flare frequency distributions of relatively low temperature G-type main sequence stars (solid line) and relatively high temperature ones (dashed line). The latter stars have a lower flare frequency by about 0.5 dex. This figure is taken from Shibayama *et al.* (2013).

asymmetric or double-lined profiles. There remains a possibility that a companion star, especially very low mass star, and/or a hot Jupiter is detected in some of these stars in future.

Notsu *et al.* (2013a) reported a spectrum of KIC 6934317, one of these 34 ‘single’ stars. Many superflares with the energy up to 2×10^{35} erg were detected on this object, and its rotation period was estimated to be 2.54 d (Shibayama *et al.* 2013). Absorption lines of Ca II 8542 and Li 6707 of this star are shown in figure 4. Ca II 8542 is regarded as an indicator of the chromospheric activity (e.g. Takeda *et al.* 2010), and KIC 6934317 certainly has an emission component in this line. On the other hand, the Li 6707 absorption line is very weak in this star.

The projected rotation velocity $v \sin i$ of KIC 6934317 is measured to be 1.9 km s^{-1} by an analysis of the absorption lines of Fe, one of which is shown in figure 4. This value is very small, compared with the rotation velocity of ~20 km s^{-1} estimated with the photometric period. This means a very low inclination of KIC 6934317. Figure 5 show a diagram of the flare amplitude vs brightness variation amplitude. If the flare energy $E_{\rm flare}$ is limited by the magnetic energy $E_{\rm mag}$ stored around a spot, the flare energy is

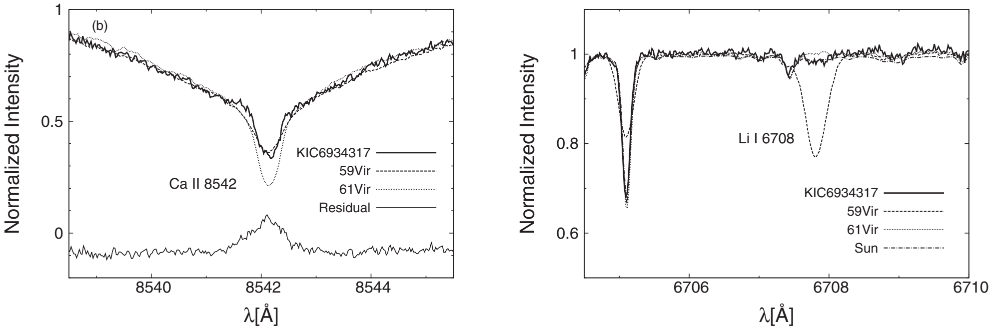

Figure 4. Absorption lines of Ca II 8542 (left panel) and Li 6708 (right panel) taken from Notsu *et al.* (2013a). KIC 6934317 is a superflare star. 59 Vir and 61 Vir are known to be a fast rotating, active star, and slowly rotating, inactive star, respectively. The residual in the left panel is obtained by subtraction of the spectrum of 61 Vir from that of KIC 6934317. KIC 6934317 has an emission component in Ca II 8542 at the same level of 59 Vir, but does not show a clear absorption component in Li 6708. The other absorption line in the right panel is Fe I 6705.

expressed by the following equation:

$$E_{\rm flare} \simeq f E_{\rm mag} \simeq f \frac{B^2}{8\pi} A^{3/2} \simeq 7 \times 10^{32}\,[{\rm erg}] \left(\frac{f}{0.1}\right) \left(\frac{B}{10^3{\rm G}}\right)^2 \left(\frac{A/2\pi R_*^2}{0.001}\right)^{3/2}, \qquad (2)$$

where f is the fraction of magnetic energy that is released as flare energy, B is the magnetic flux density of the spot, and A is the area of the spot (Shibata *et al.* 2013; see also Shibata *et al.* 2016). The solid line indicates the upper limit ($f = 1$) of the magnetic energy on the assumption that the fraction of the spot area to the stellar disk is equal to the brightness variation amplitude, and that the magnetic flux of the spot is $B = 1,000$ G, the typical B value of the sunspot. If the inclination is low, the brightness amplitude become small. In an extreme case of $i = 0°$ (pole-on), the brightness amplitude is 0. KIC 6934317 is located near the dashed line of $i = 2°$, being consistent with its small projected rotational velocity. Note that this may by also explained by multi spots and/or large magnetic density.

Nogami *et al.* (2014) suggested that two superflare stars KIC 9766237 and KIC 9944137 have stellar parameters very similar to those of the Sun in terms of the effective temperature, surface gravity, and metallicity (see figure 6), though the Ca II IR triplet absorption line indicates that the chromospheric activity of these stars are slightly higher than that of the Sun. They are slow rotators, $P_{\rm rot}$ = 21.8 and 25.3 day for KIC 9766237 and 9944137, respectively (Shibayama *et al.* 2013). These results support the hypothesis that the Sun may cause superflares. Though the rotation period of KIC 9766237 and 9944137 is revised to be 14.2 and 12.6 day, respectively (Notsu *et al.* 2015b), the orbital period is still over 10 days and they are not young stars.

Honda *et al.* (2015) investigated the lithium abundances L(Li) and its correlation with other stellar parameters. The accurate spectroscopic determination of the lithium abundance provides independent and reliable age diagnostics (e.g. Duncan 1981). Figure 7 shows scatter diagrams of A(Li)-$v \sin i$ and A(Li)-r_0(8542), where the index r_0(8542) is the normalized intensity of the line center of Ca II 8542. We can see a trend that higher lithium-abundance stars have higher $v \sin i$ values. There is no large difference between the distribution of field stars and that of superflare stars, though superflare stars may tend to have higher $v \sin i$ values for A(Li). An exception KIC 11764567, which has large $v \sin i$ and log A(Li), might be a binary system (see Honda *et al.* 2015). In the right panel

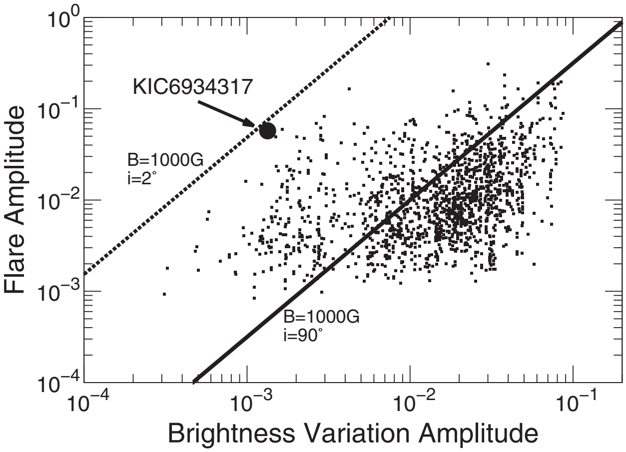

Figure 5. Flare amplitude - brightness variation amplitude diagram taken from Notsu *et al.* (2013a). KIC 6934317 has a relatively large flare amplitude for its brightness variation amplitude, which is regarded as a result from that the brightness variation amplitude apparently become small with a small inclination.

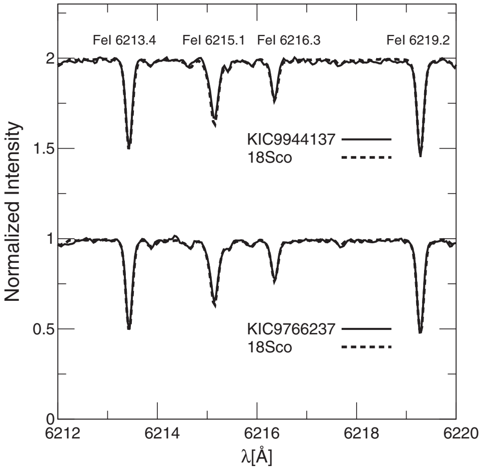

Figure 6. Example of photospheric absorption lines, including Fe I 6213, 6215, 6216, and 6219 of KIC 9766237, KIC 9944137, and 18 Sco (the solar twin star) taken from Nogami *et al.* (2014). The profiles of these lines on these superflare stars are in good agreement with those of 18 Sco, suggesting that these stars have similar stellar parameters.

of figure 7, the $r_0(8542)$ index of superflare stars has higher values for $A(\mathrm{Li})$ than that of field stars, which seems natural since they are superflare stars.

The scatter diagram of $A(\mathrm{Li})$ and the number of detected superflares on each star is shown in figure 8. There is no trend or a weak trend of an $A(\mathrm{Li})$ decrease with an increase of the number of superflares. A possibility of ^{6}Li production by stellar flares is suggested by Tatischeff & Thibaud (2007), but it is not supported by this result.

4. Conclusion

We have discovered about 1500 superflares on about 300 superflare G-type main sequence stars in the Kepler data. Even old, slow rotator dwarf like the Sun may cause superflares with energy of 10^{35} ergs once in 5000 years. High dispersion spectroscopy

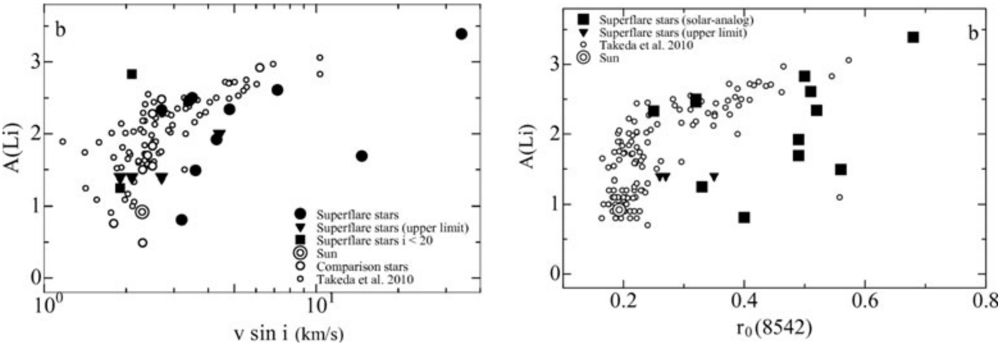

Figure 7. A(Li)-$v \sin i$ diagram (left panel) and A(Li)-r_0(8542) diagram (right panel) taken from Honda *et al.* (2015). Filled and open marks represents data of superflare stars and field solar-analog stars, respectively. Filled triangles represent upper limits. In this figure, we used the data of superflare stars having the temperature T between 5,500 K and 6,000 K, since lower temperature stars (T ¡ 5,500 K) have a deeper convection layer and tend to show lower Li abundances. There is no large difference between the distribution of superflare stars and that of field stars. In the right panel, we can see most of superflare stars have larger values of the r_0(8542) for the same A(Li).

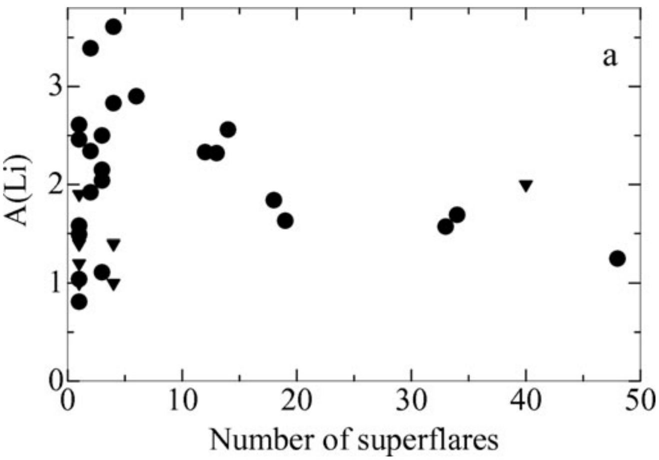

Figure 8. Li abundance distribution against the number of the superflare. Filled triangles represent upper limits. Even most active stars do not have a high Li abundance. This figure is taken from Honda *et al.* (2015).

suggests that more than half of superflare stars do not show evidence of binary, and indicates high chromospheric activity and existence of large spots. Some superflare stars are proved to have stellar parameters very similar to those of the Sun. All of these facts supports a possibility that the Sun can cause a superflare. It is important to monitor many superflare stars and 'normal' solar-type stars and clarify changes of their activities.

Acknowledgement

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