Superflares on the slowly rotating solar-type stars KIC10524994 and KIC07133671?

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ABSTRACT
An investigation of the G-type stellar population with Kepler (as done by Maehara et al.) shows that less than 1 per cent of those stars show superflares. Due to the large pixel scale of Kepler ($\approx 4$ arcsec px$^{-1}$), it is still not clear whether the detected superflares really occur on the G-type stars. Knowing the origin of such large brightenings is important to study their frequency statistics, which are uncertain due to the low number of sun-like stars ($T_{\text{eff}} = 5600$–6000 K and $P_{\text{rot}} > 10$ d) which are currently considered to exhibit superflares. We present a complete Kepler data analysis of the sun-like stars KIC10524994 and KIC07133671 (the only two stars within this subsample of solar twins with flare energies larger than $10^{35}$ erg; Maehara et al.), regarding superflare properties and a study about their origin. We could detect four new superflares within the epoch Maehara et al. investigated and found 14 superflares in the remaining light curve for KIC10524994. Astrometric Kepler data of KIC07133671 show that the photocentre is shifted by 0.006 px or 25 mas during the one detected flare. Hence, the flare probably originated from another star directed towards the north-east. This lowers the superflare rate of sun-like stars (and hence the Sun) for $E > 10^{35}$ erg, since this additional star is probably not solar-like.

Key words: Sun: activity – Sun: flares – stars: flare – stars: solar-type – starspots.

1 INTRODUCTION
Stellar flares are defined as rapid brightenings of emission across the electromagnetic spectrum (Benz 2008), typically followed by an exponential relaxation back to the quiescent state of a star. It is assumed that such brightenings are caused by the release of magnetic energy, which is stored near active regions in the stellar photosphere. Our Sun shows flares with typical energies of $10^{24}$–$10^{30}$ erg (Aschwanden et al. 2000; Schrijver et al. 2012). A study of the spectral content of solar flares (Kretzschmar 2011) indicates that the optical part of the spectrum can be well approximated by a blackbody radiation with $\sim 10,000$ K.

A variety of stars show flares with energies $\geq 10$ times that of the largest known solar event ($10^{22}$ erg), that are therefore called ‘superflares’ (Schaefer, King & Deliyannis 2000). It is expected that superflares occur more frequently on magnetically active K- and M-type dwarfs, which are mostly fast rotators and partly full convective (Maehara et al. 2012). Nevertheless, there is a small number of stars, presumably like the Sun, that show superflares. These stars are on or near the main sequence, have spectral types F8–G8 with corresponding temperatures $5100 \leq T_{\text{eff}} < 6000$ K, and are not young. A study of all the suitable stars within the Kepler Input Catalogue (KIC; Brown et al. 2011) shows that the fraction of superflare stars among such ‘solar-like’ stars is about 0.5 per cent (Maehara et al. 2012). This value must be treated with care, since flares can also be caused by close binary interaction, wide late-type companions or other scenarios. If such superflare stars are really solar twins, one might conclude upon the frequency and energetics of superflares on the Sun.

Solar superflares with energies above $10^{35}$ erg could be harmful to the biosphere and also very relevant for space weather. It was discussed recently whether the AD 774/5 $^{14}$C event was due to a solar superflare (Miyake et al. 2012). Since the activity of the Sun as known from historic sunspot and aurora observations is known only for up to 2–3 millennia, the rate of solar superflares is also not well known. In Intcal $^{14}$C data, there were three large spikes within the last 3000 yr (Miyake et al. 2012), but their origin is not known. Better constraints can be obtained from the rate of superflares of many sun-like stars.

In this work, we reanalyzed the light curves of two interesting superflare stars, KIC10524994 and KIC07133671, found by Maehara et al. (2012), that have the highest flare energies within the subsample of presumably sun-like stars with temperatures $5600 \leq T_{\text{eff}} < 6000$ K, and probably long rotational periods ($> 10$ d).
We investigated the origin of the superflares directly from Kepler Photometry (Section 2.1) and Kepler Astrometry (Section 2.5) and indirectly from the occurrence times of the detected flares (Section 2.3). Additionally, we characterized all detected flares regarding their energies and luminosities (Section 2.4), determined a power law for the frequency of superflares \( > 10^{34} \text{erg} \) (Section 2.6) and we estimated the ages of the stars for a comparison with the Sun (Section 2.2).
2 DATA ANALYSIS AND RESULTS

We used the Multimission Archive at Space Telescope Science Institute\(^1\) to retrieve the light-curve and target-pixel files (TPF) for each quarter. The light-curve files contain exposure times, aperture photometry fluxes (SAP) with photometric errors and fluxes corrected for pointing errors, focus changes and thermal effects (PDC-SAP; Jenkins et al. 2010). In the TPFs, pixel data are presented as a time series of photometrically calibrated images, while the pixels are assigned either to the optimal aperture or a halo around it (Kinemuchi et al. 2012).

2.1 Origin of photometric variability

Figs 1 and 2 show the Pre-Data-Conditioning single aperture photometry (PDC-SAP) fluxes of KIC10524994 and KIC07133671 for each quarter. While there are 16 quarters available for KIC10524994, only 3 quarters could be gathered from the archive in the case of KIC07133671.

If we are visually looking at the quarterly light curves of KIC10524994 (Fig. 1), most of them show quasi-periodic brightness variations with an irregular modulation in amplitude of up to 40 mmag. A simple estimation shows that the averaged amplitude of these variations can be explained by stellar spots that have a slightly different temperature than the photosphere (Fig. 3). If one considers similar spot temperatures as those for the Sun, which means \(\approx 4500\) K for umbrae (Chaisson & McMillan 1999), a single spot would cover about 4 percent of the visible hemisphere, which is a realistic scenario. In contrast to binary eclipses with an expected constant amplitude, stellar spots can be variable regarding their spot size and temperature, while new spots can be generated at other longitudes and latitudes, hence one can explain the observed phase jumps (due to differential rotation) and amplitude shifts.

Although the hypothesis of binary eclipses cannot be ruled out for sure, we assume that the frequency of the most dominant light-curve variation corresponds to the rotational period of the star. We used the Lomb–Scargle method (LSP) to calculate the spectral content of the signal. Rotational periods were estimated from the mean of a Gaussian shape, which was fitted to the highest peak of the power spectrum. We then compared the results of Lomb–Scargle Periodogram (LSP) with the results from computing the ‘string length’ (Dworetsky 1983). We normalized the magnitudes (\(m_i\)) and transformed all times into phases (\(\phi_i\)) that correspond to a particular period. We used the period for which the sum of the lengths of line

\(^1\) http://archive.stsci.edu/kepler/

Figure 2. Quarter light curves of KIC07133671 for quarter 0–2 of public Kepler data. The vertical line denotes the position of one detected superflare (see Table 2). Most of the light-curve variations can be explained by a set of ‘cotrending basis vectors’ (Smith et al. 2012), which were designed to describe the most common trends for all Kepler field-of-view stars, caused by the spacecraft operation.

Figure 3. Normalized spot size as a function of spot temperature for a central circular spot for KIC10524994. Spots across the solid line would induce brightness variations of the star equal to the \(4\sigma\) range of the light-curve variation due to their movement with the rotation of the star. We modelled the projected disc of the star with a linear limb-darkening law (Claret 2000) while the spot area was weighted with \((T_{\text{spot}}/T_{\text{star}})^4\). Within the \(1\sigma\) range of \(T\) (grey zone), the spot size decreases to less than 20 per cent of the stellar hemisphere.

Figure 4. LSP of quarter 8 of KIC10524994. A period of \(P_{\text{rot}} = (11.84 \pm 0.53)\) d could be estimated from a Gaussian fit of the highest peak. Additionally to this main peak, one harmonic of that period at about 5.98 d is detected. For a better resolution, only the period range up to 25 d is shown, but was computed up to 50 d.
segments between neighbouring points \((m_i, \phi_i)\) is minimized as the true period.

From the LSP, we got a period of \(P_{\text{rot}} = (11.84 \pm 0.53)\) d for KIC10524994 (Fig. 4), which is consistent with the value of Maehara et al. (2012).

We computed the string length for a spectral range between 1 and 50 d with a step rate of \(2 \times 10^{-5} \text{d}^{-1}\) in the frequency domain. Independent of the Lomb–Scargle method, a rotational period of \(P_{\text{rot}} = (11.87 \pm 0.07)\) d could be determined, which is consistent with LSP. Fig. 5 shows the phase folded and binned light curve of KIC10524994 for quarter 8, which contains of the most stable amplitude.

From the light-curve shape in Fig. 5, one can rule out some hypotheses. If the shape were caused by eclipses of a binary, the disappearance of phases with constant flux would categorize the companion as a giant; hence, it would dominate the spectral class of the system. An eclipsing binary in the background can be responsible for the amplitude, but it cannot explain the brightness modulation in the different quarters and it is less realistic that such an amplitude is created by star-spots of a single background star.

The sinusoidal like light-curve shape supports the hypothesis of large star-spots on the stellar surface of KIC10524994 but nevertheless, the possibility of an unresolved binary or a combination of both eclipses and stellar spots remains.

The basic counting error for KIC10524994 is about 0.04 per cent of the mean flux level (0.03 per cent for KIC07133671). Binned data points in Figs 5 and 6 represent the weighted means for each set of data points that fall within a certain phase bin and the size of the error bars corresponds to their uncertainty. Since stellar spots can evolve rapidly during an observational quarter, data points of slightly different magnitudes and phase ranges might be combined here. The occurrence phases of the detected superflares are well distributed over the entire phase range, as illustrated in Figs 5 and 6 by diamonds.

The quarter light curves of KIC07133671 are not quasi-periodic and most of the artefacts, plotted in Fig. 2, can be explained by ‘cotrending basis vectors’ (Smith et al. 2012), that were designed to describe the most common trends of all \textit{Kepler} targets. Hence, the light-curve variations are not intrinsic features of the target. Nevertheless, we detected a period of \(P = (15.19 \pm 0.85)\) d with the ‘string-length’ method (Dworetsky 1983), which is consistent with the rotational period found by Shibayama et al. (2013). From the light-curve shape (Fig. 6), one cannot distinguish between an eclipsing binary or a star-spot modulation. The brightness variation is up to 0.6 mmag.

### 2.2 Age determination from rotational periods

We used rotational periods to roughly estimate the ages of the stars. The upper limit was determined by a comparison with evolutionary models of the angular momentum as described in Bouvier, Forestini & Allain (1997). The main assumptions of this model are solid body rotation and interaction of the stellar surface with the time-dependent appearance of a circumstellar disc (Bouvier et al. 1997). A rotational period of 11.87 d (for solar radius) for KIC10524994 is consistent with a surface angular velocity of \(\Omega \approx 2\Omega_\odot\). According to fig. 4 in Bouvier et al. (1997), we estimate an age of \(\approx 1.0^{+0.6}_{-0.4}\) Gyr for KIC10524994, so that KIC10524994 might be less than one order of magnitude younger than the Sun.

For KIC07133671, we do not estimate the age since it is very unlikely that the determined period is the rotation period of the star. A lower limit was estimated from proper motion measurements (Roeser, Demleitner & Schilbach 2010) for both stars (see therefore Section 2.5).

### 2.3 Flaring rate and cyclic behaviour

Maehara et al. (2012) analysed calibrated long-cadence \textit{Kepler} flux time series of the first three quarters. The distribution of brightness changes between all pairs of two consecutive points were calculated to define a statistical threshold of a superflare event. The typical value of this threshold is about 0.1 per cent of the brightness of the stars in the \textit{Kepler} filter response. In this work, the analysis was extended to all available and public data of the first 16 quarters. To search for superflares and additionally smaller flares, we first smoothed the light curves with a 6th level discrete wavelet transformation. This works as a high-pass filter that eliminates all intrinsic brightness variations with periods >32 h while leaving all short-time variabilities unaffected. Since a typical flare lasts only a few hours, this does not influence the superflare analysis.
Then, a Bayesian Analysis for Change Point Problems (Barry & Hartigan 1993) was applied to the smoothed light curves. This analysis presents the probabilities of a sudden variation of the brightness for each time stamp of a light curve. Data points with a high probability for a sudden change (>50 per cent) were fitted with a mathematical expression that is equivalent to a polynomial rising part and an exponential decay

\[
F(t) = \begin{cases} 
F_0 + B \times (t-t_1)^2 & t \leq t_2 \\
F_0 + A \times e^{-(t-t_3)/\alpha} & t \geq t_2
\end{cases}
\]  

(1)
to identify all the flares. \(F_0\) is the normalized flux, \(A\) is the flare amplitude, \(\alpha\) describes the power law of impulsive phase, \(t_1, 2\) denote the flare start and peak time, and \(t_2\) is a decay constant that corresponds to the duration of the flare. These parameters were optimized with a Levenberg–Marquardt routine and a simple F-Test with a commonly used 95 per cent-confidence interval was applied to compare our result with a constant model.

We could detect four new superflares during the observing epoch Maehara et al. (2012) investigated and 14 additional new superflares in the remaining quarters for KIC10524994 (in total 19 superflares) by performing a Change Point analysis (Barry & Hartigan 1993) with 1000 iterations to consecutive segments of the light curves with lengths of 4 d. For KIC07133671, we could detect one superflare, the one observed by Maehara et al. (2012). Each single flare is shown in Fig. 7. The occurrence times of these flares were used to investigate any cyclic properties. It is possible that close binaries and additional ‘hot Jupiters’ in eccentric orbits can cause superflares by strong magnetic interaction with their host stars (Rubenstein & Schaefer 2000). In this case, one might expect a periodic behaviour of the flare frequency that could be higher during the passage of periaster and lower in the remaining orbit. We used the method of Gregory & Loredo (1992) to compare a constant model with the hypothesis of a periodic intensity rate. From these calculations, we cannot confirm a close companion around KIC10524994, which might be biased by the low number of detected flares. Additionally, we have not detected planetary transits among our targets.

2.4 Flare properties

All detected flares and superflares with their fitting parameters could be used for further characterization. We were interested in the distribution of bolometric flare luminosities, energies and their influence on the waiting time between two consecutive events. If one observes only in one pass band, one cannot determine the spectral content of flares. Moreover, observations on the Sun indicate that the spectral composition of radiated flare energy is a function of time, since the light-curve shape of a flare is different when observing in different pass bands (Benz 2008). We simplified the complex behaviour of a flare event to be an emission of a blackbody radiation, as suggested by Kretzschmar (2011) to estimate bolometric flare energies and luminosities. We assumed higher temperatures of the black bodies than the stellar photosphere and therefore calculated bolometric flare energies and luminosities representative for 6000, 10 000 and 20 000 K. Values in Table 2 are calculated for 10 000 K. Values for 6000 and 20 000 K can be derived by scaling factors of 0.82 and 4.79, respectively.

To calculate bolometric flare energies and luminosities, additional data can be obtained from Table 1. The procedure is as follows: we calculated luminosities and absolute brightnesses of the stars. Bolometric corrections (BC) were done in K band using the closest grid point \((T_{\text{eff}}, \log g)\) from published BC coefficients of Bessell, Castelli & Plez (1998). For the flares, we considered the spectral response of the Kepler photometer. BC were done after transforming \(m_{BOL}^{\text{Kep}}\) into \(V\) (Still et al. 2011). Due to uncertainties of \(R_{\text{star}}\) and \(T_{\text{eff}}\), given in the KIC, the expected errors of these calculations are up to 85 per cent. The values for bolometric flare luminosity and energy are presented in Table 2. For the flares detected in the light curve of KIC10524994, we further investigated the correlation between the flare energy and the cadence of two neighbouring events. All the detected flares are superflares, according to their \(1\sigma\) errors and the definition by Schaefer et al. (2000), which is at least 10 times the energy of the largest known solar event \((10^{32} \text{erg})\). For most of the superflares, the waiting time is less than 100 d, but we could not find any dependence on the flares energies.

Table 1. KIC Data for KIC10524994 and KIC07133671. All the quantities could be derived from \(T_{\text{eff}}\) and \(\log g\). Their uncertainties are estimated to be ±200 K and ±0.3 dex (Brown et al. 2011).

|          | KIC10524994 | KIC07133671 |
|----------|-------------|-------------|
| \(T_{\text{eff}}\) [K] | 5747 ± 200 | 5657 ± 200 |
| \(R_{\text{star}}\) [R\(_{\odot}\)] | 0.971 ± 0.335 | 1.140 ± 0.394 |
| \(m(g)\) [dex] | 4.5 ± 0.3 | 4.4 ± 0.3 |
| \(m_{BOL}^{\text{Kep}}\) | 15.34 ± 0.03 | 15.47 ± 0.03 |
| \(m_{\text{mag}}\) | 13.47 ± 0.04 | 13.57 ± 0.06 |
| \(A_V\) [mag] | 0.402 | 0.581 |

Table 2. List of all detected flares (Fig. 7) with their occurrence time, bolometric luminosity, energy, and equivalent duration \(d_{\text{eq}}\) for KIC10524994 and KIC07133671 (values for a 10 000 K blackbody radiation). The flare energy was calculated by integrating the estimated luminosity over time from the start to the end of the flare. The end of the flare was determined by F-Test statistics.

| # | MBJD\(^2\) (d) | \(L_{\text{bol}}\) (10\(^{32}\) \text{erg s}^{-1}) | \(E_{\text{bol}}\) (10\(^{35}\) \text{erg}) | \(d_{\text{eq}}\) (s) |
|---|---------------|----------------|----------------|----------------|
| 1 | 96.06 | 1.05 ± 0.93 | 2.68 ± 2.38 | 74.66 |
| 2 | 113.89 | 0.30 ± 0.26 | 0.88 ± 0.78 | 24.45 |
| 3 | 212.80 | 0.12 ± 0.11 | 0.38 ± 0.34 | 10.51 |
| 4 | 220.58 | 0.27 ± 0.24 | 1.34 ± 1.19 | 37.44 |
| 5 | 256.81 | 0.19 ± 0.17 | 0.43 ± 0.39 | 12.08 |
| 6 | 334.14 | 0.34 ± 0.30 | 1.04 ± 0.92 | 28.96 |
| 7 | 414.15 | 0.16 ± 0.14 | 0.50 ± 0.44 | 13.90 |
| 8 | 465.52 | 0.46 ± 0.41 | 1.09 ± 0.97 | 30.54 |
| 9 | 485.33 | 0.15 ± 0.13 | 1.32 ± 1.18 | 36.87 |
| 10 | 535.51 | 0.21 ± 0.19 | 0.75 ± 0.67 | 20.94 |
| 11 | 601.45 | 0.44 ± 0.39 | 1.58 ± 1.40 | 44.06 |
| 12 | 670.18 | 0.16 ± 0.14 | 1.73 ± 1.54 | 48.34 |
| 13 | 680.74 | 0.25 ± 0.22 | 0.55 ± 0.49 | 15.42 |
| 14 | 745.56 | 0.15 ± 0.13 | 0.35 ± 0.31 | 9.83 |
| 15 | 755.06 | 0.33 ± 0.29 | 1.03 ± 0.92 | 28.85 |
| 16 | 878.12 | 0.19 ± 0.17 | 0.57 ± 0.51 | 16.03 |
| 17 | 1007.61 | 0.15 ± 0.13 | 0.85 ± 0.75 | 23.61 |
| 18 | 1248.73 | 0.35 ± 0.31 | 1.21 ± 1.07 | 33.67 |
| 19 | 1442.65 | 0.28 ± 0.25 | 0.88 ± 0.78 | 24.60 |

\(^2\) MBJD = BJD − 245 4900 [d].
Figure 7. Detected flares in the light curves of KIC07133671 (lower right) and KIC10524994 (all others, see also Table 2). The normalized fluxes are plotted over time. All the flares were fitted with a Levenberg–Marquardt optimization routine. Due to the time resolution of 29.4 min between consecutive data points, only flares with a duration longer than about 30 min could be detected. It is therefore expected that the stars have many more flares on shorter time-scales.

2.5 Kepler astrometry

We used the TPF files of the targets to calculate their astrometric signal. For each time stamp, the files provide a fully calibrated array of pixel fluxes, their $1\sigma$ uncertainties, information about cosmic ray incidences and a predicted motion of the targets calculated from the motion of a set of reference stars on the detector (Kinemuchi et al. 2012). Monet et al. (2010) showed that the precision of a single measurement of a typical star can be as good as 0.001 pixel. The pixel scale of Kepler is about 4 arcsec px$^{-1}$. If one assumes the target stars are unresolved point sources, the signal of a flare would be well distributed over the optimal aperture of the target; hence, the centre of light would not be changed significantly by a flare. Note that it is not unusual for Kepler targets that a pixel mask is crowded by the flux of neighbouring stars. If flares are produced on such other sources, the centre of light could change significantly towards the source of the brightening. Therefore, we convolved the astrometric signal of the stars with the occurrence times of detected flares to test the hypothesis of a crowded field.

We used a simple centre approximation (Howell 2006) for the point spread function (PSF) of the target to calculate the centre of light and error bars for each time stamp for both detector axes using the calibrated pixel fluxes. After subtracting the predicted movement from the raw astrometric signal, the shift on the detector is mostly linearized. This movement might be a superposition of proper motion and trigonometric parallax, but can still contain a signal from binary interaction or differential velocity aberration (Monet et al. 2010). We fitted a second-order polynomial to the curve to eliminate this remaining trend.

Figs 8 and 9 show a contour plot for the centre of light for KIC10524994 and KIC07133671 on the detector. The grey levels represent the location density of the stars during quarter 0 in terms of the number of positions per square millipixel. For each star, we overplotted the astrometric signal at the peak time $\pm 2\text{ min}$ for the
shows a histogram of the cumulative frequency distribution 
∝ 442, 2012 = 2012 μ 10 2012 10 (± 34 1.2 ± (−3.8) mas yr) erg).

For this purpose, we tried to fit with a 1.2). It fits well to the frequency distribution localization density for KIC10524994 for quarter 0 after move-

distance from the averaged photometric barycentre. This is σ levels for a fit to the distribution of the surrounding stars. Since we have no indication for membership in any open clusters from the proper motion measurements, we assume that the targets are not younger than 1 Gyr, as this is the upper time-scale over which a cluster is typically disrupted (de La Fuente Marcos 1998).

2.6 The frequency distribution of superflares for energies > 10^{34} erg

We used the energy distribution of the superflares of KIC10524994 to determine the cumulative frequency distribution (f) for bolometric flare fluences above 10^{34} erg. For this purpose, we tried to fit with a power law f ∝ E^{−\alpha}, as done by Schrijver et al. (2012) for solar flares. Fig. 10 shows a histogram of the cumulative frequency distribution in units per time over the energy for superflares on the G-type star KIC10524994. The size of the energy bins is comparable to the averaged uncertainty of the superflare energies. With a Levenberg–Marquardt optimization routine, we fitted a power law with an index of \(\alpha = 1.2 ± 0.2\) (see Fig. 10, solid line). It is interesting to note, that this power-law index for KIC10524994 is consistent with the value estimated by Schrijver et al. (2012) for solar flares of much lower energies (10^{31}–10^{37} erg).

3 DISCUSSION

We could show that the frequency of superflares on KIC10524994 can be well described by a power-law index of \(\alpha = 1.2\). This is consistent with the power-law index of solar flares in a much lower energy range (Schrijver et al. 2012). In order to improve the frequency statistics and to connect both energy ranges of the known solar flares and the superflares on sun-like stars by a certain power-law approximation, more sun-like stars need to be investigated with our detection and analysing method. Note that the superflare energies in this work are roughly 2–3 times larger than in Maehara et al. (2012), since Maehara et al. (2012) did not include extinction in the energy calculations.
KIC10524994 and KIC07133671 were the only two presumable sun-like stars within an investigated sample of 14,000 stars that show superflares with energies larger than $10^{35}$ erg (Maehara et al. 2012). On the basis of only these two stars, Maehara et al. (2012) estimated a frequency of one flare in 5000 yr for that energy range.

Since the photocentre of the emission is shifted only during the (only one observed) flare of the star KIC07133671, the flare did not originate on this solar-like star, but on a background or companion star. Hence, KIC07133671 should not be included in the statistics of superflares of sun-like stars — reducing the rate of Maehara et al. (2012) by a factor of 2. Hence, the probability for the AD 774/5 event (Miyake et al. 2012; Hambaryan & Neuhäuser 2013) to be a solar superflare also is smaller than previously thought. The other presumable solar-like superflare star, KIC10524994, may be still a close binary with separation smaller than the Kepler PSF.

Kepler astrometry is a powerful tool to check whether a target pixel mask is crowded by error sources, e.g. background objects, that could be the origin for detected superflares. Though we only investigated the light curves of two stars, the rejection of KIC07133671 as a superflare star has a high impact on the frequency statistics of that energy range. This yields additional motivation for applying our method to the remaining superflare stars, probably to find more false positives, and hence, to further improve the frequency statistics. This is also necessary to find constraints for superflares on the Sun.

4 SUMMARY

The light curves of two superflare stars, KIC07133671 and KIC10524994, were analysed to detect and characterize superflares. We further investigated the cyclic behaviour of the detected flares to check the hypothesis of possible companions indirectly. For KIC10524994, we could find a rotational period of $(11.87 \pm 0.07)$ d, which is compatible with Maehara et al. (2012). This period was compared to evolutionary models of the surface angular velocity. We could derive an age of $1.0^{+0.6}_{-0.4}$ Gyr, which is only a rough estimate. With a Bayesian approach, we could detect 19 flares, while 18 of them are new detections, compared to Maehara et al. (2012). For KIC07133671, we could find a period of $15.19$ d, which is consistent with Shibayama et al. (2013). We could find one superflare for KIC07133671, the one from Maehara et al. (2012). From the convolution of the astrometric signal of KIC07133671 with the occurrence time of its flare, there is high evidence that the flare is caused by a background star or a companion, indicating that the target should not be involved in the frequency statistics of superflares of solar twins.

We determined the frequency of superflares in the energy range of $10^{34}-10^{35}$ erg by a power law with an index of $\alpha = 1.2 \pm 0.2$. A comparison to solar flares of much lower energies indicates that the distribution of solar flares and the distribution of superflares on KIC10524994 are assigned to the same power-law index (Schrijver et al. 2012). To improve the frequency statistics and to find constraints for superflares on the Sun, we plan to reanalyse all the sun-like stars within the population that Maehara et al. (2012) investigated.

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REFERENCES

Aschwanden M. J., Tarbell T. D., Nightingale R. W., Schrijver C. J., Title A., Kankelborg C. C., Martens P., Warren H. P., 2000, ApJ, 535, 1047
Barry D., Hartigan J. A., 1993, J. Am. Stat. Assoc., 88, 421, 309
Benz A. O., 2008, Living Rev. Sol. Phys., 5, 1
Bessell M. S., Castelli F., Plez B., 1998, A&A, 333, 231
Bouvier J., Forestini M., Allain S., 1997, A&A, 326, 1023
Brown T. M., Latham D. W., Everett M. E., Esquerdo G. A., 2011, ApJ, 142, 112
Chaisson E., McMillan S., 2005, Astronomy Today, Volume 1: The Solar System, 5th ed. Prentice Hall (ISBN 0-13-117683-8)
Claret A., 2000, A&A, 363, 1081
de La Fuente Marcos R., 1998, PASP, 110, 1117
Dworetzky M. M., 1983, MNRAS, 203, 917
Gregory P. C., Loredo T. J., 1992, ApJ, 398, 146
Hambaryan V. V., Neuhäuser R., 2013, MNRAS, 430, 32
Howell S. B., 2006, Handbook of CCD astronomy, 2nd ed., Vol. 5. Cambridge Univ. Press, Cambridge (ISBN 0521852153)
Jenkins J. M. et al., 2010, ApJ, 713, L87
Kinemuchi K., Barclay T., Fanelli M., Pepper J., Still M., Howell S. B., 2012, PASP, 124, 963
Kretzschmar M., 2011, A&A, 530, 84
Maehara H. et al., 2012, Nature, 485, 478
Miyake F., Nagaya K., Masuda K., Nakamura T., 2012, Nature, 486, 240
Monet D. G., Jenkins J. M., Dunham E. W., Bryson S. T., Gilliland R. L., Latham D. W., Borucki W. J., Koch D. G., 2010, Preliminary Astrometric Results from Kepler, preprint (arXiv:1001.0305)
Roeser S., Demleitner M., Schilbach E., 2010, AJ, 139, 2440
Rubenstein E. P., Schaefer B. E., 2000, ApJ, 529, 1031
Schaefer B. E., King J. R., Deliyannis C. P., 2000, ApJ, 529, 1026
Schrijver C. J. et al., 2012, J. Geophys. Res., 117, 8103
Shibayama T. et al., 2013, ApJ, 209, 5
Smith J. C. et al., 2012, PASP, 124, 1000
Still M. D., Fanelli M., Kinemuchi K. Kepler Science Team, 2011, BAAS, 43, 140.02

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