Superflares on the late-type giant KIC 2852961

Scaling effect behind flaring at different energy levels

Zs. Kővári¹, K. Oláh¹, M. N. Günther²,*, K. Vida¹,³, L. Kriskovics¹,³, B. Seli¹, G. Á. Bakos⁴, J. D. Hartman⁴, Z. Csubry⁴, and W. Bhatti⁴

¹ Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Budapest, Hungary
e-mail: kovari@konkoly.hu
² Department of Physics, and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
³ ELTE István Loránd University, Institute of Physics, Budapest, Hungary
⁴ Department of Astrophysical Sciences, Princeton University, NJ 08544, USA

ABSTRACT

Context. The most powerful superflares reaching 10³⁹ erg bolometric energy are from giant stars. The mechanism behind flaring is supposed to be the magnetic reconnection, which is closely related to magnetic activity including starspots. However, it is poorly understood, how the underlying magnetic dynamo works and how the flare activity is related to the stellar properties which eventually control the dynamo action.

Aims. We analyse the flaring activity of KIC 2852961, a late-type giant star, in order to understand how the flare statistics are related to that of other stars with flares and superflares and what the role of the observed stellar properties in generating flares is.

Methods. We search for flares in the full Kepler dataset of KIC 2852961 by an automated technique together with visual inspection. We cross-match the flare-like events detected by the two different approaches and set a final list of 59 verified flares during the observing term. We calculate flare energies for the sample and perform a statistical analysis.

Results. The stellar properties of KIC 2852961 are revised and a more consistent set of parameters are proposed. The cumulative flare energy distribution can be characterized by a broken power-law, i.e. on the log-log representation the distribution function is fitted by two linear functions with different slopes, depending on the energy range fitted. We find that the total flare energy integrated over a few rotation periods correlates with the average amplitude of the rotational modulation due to starspots.

Conclusions. Flares and superflares seem to be the result of the same physical mechanism at different energetic levels, also implying that late-type stars in the main sequence and flaring giant stars have the same underlying physical process for emitting flares. There might be a scaling effect behind generating flares and superflares in the sense that the higher the magnetic activity the higher the overall magnetic energy released by flares and/or superflares.

Key words. Stars: activity – Stars: flare – Stars: late-type – Stars: individual: KIC 2852961, 2MASS J19261136+3803107, TIC 137220334

1. Introduction

Studying the cosmic neighborhood of magnetically active stars, i.e., the impact of stellar magnetism on the circumstellar environment, where planets may revolve, is currently a hot issue. Stellar flares can heavily affect their close vicinity, such like the solar flares affect the Earth. The most energetic solar flares recorded so far, e.g. the “Carrington Event” in 1859, reached the energy output of 10³⁳ erg. On the other hand, stellar flares can release one to six orders of magnitude more energy (Maehara et al. 2012) compared to the most powerful X-class solar flares; such “superflare stars” are mostly among solar-like stars from the main sequence, but can also be evolved stars in some measure, being either single or member of a binary system (see, e.g. Balona 2015, Katsova et al. 2018, Notsu et al. 2019, and their references).

The high magnetic energy outbursts by flares supposedly originate from magnetic reconnection, which presumes an underlying dynamo action, i.e. rotation/differential rotation interfering with convective motions. However, through stellar evolution slower rotation and increased size are expected to result in weaker magnetic fields and therefore lower level of magnetic activity for evolved stars compared with their main-sequence progenitors. Yet, the most powerful superflares are from giants (Balona 2015). Just recently, cross-matching superflare stars from the Kepler catalogue with the Gaia DR-2 stellar radius estimates has shown that more than 40% of the previously supposed solar-type flare stars were subgiants (Notsu et al. 2019). Magnetic activity is present and can indeed be strong along the red giant branch, which has been verified by direct imaging of starspots on the K-giant ζ Andromedae (Roettenbacher et al. 2016). However, it is not clear what kind of mechanism could generate sufficient energy to provide the most powerful superflares on giant stars. It is quite certain that in some cases binarity plays a key role: a close companion star or a close-in giant planet could mediate magnetic reconnection and so provoke superflares (Ferreira 1998, Rubenstein & Schaefer 2000, Katsova et al. 2018) proposed a magnetic dynamo working with antisolar differential rotation to explain the production of the most powerful superflares on giant stars. This is supported by the find-
ing that only giant stars were reported so far to exhibit antisolar differential rotation (see Kovári et al. [2017a] and their references). But beside the non-uniform rotation profile, convective turbulence should also play a crucial role in driving stellar dynamos. Just recently, Lehtinen et al. (2020) have demonstrated that a common dynamo scaling can be achieved for late-type main sequence and evolved, post-main-sequence stars only when both stellar rotation and convection are taken into account. This finding infers that magnetic dynamo action related flares in solar-type stars and superflares, for instance, in late-type giants can be linked by scaling as well. The paradigm that dynamo action is necessary to produce flares, however, is nuanced by the recent finding that A-type stars without convective bulk can also have superflares (Balona 2015).

Observing flares in giant stars from the ground is quite a challenge, first of all, because of the luminous background of the stellar surface. The most energetic flares of 10^33 erg in the optical range would rise the brightness level of a red giant by only a few hundredth magnitude at the peak. Such a small change is in the order of the brightness variability due to short-term redistribution of starspots, i.e., generally flares in spotted giant stars can easily be indistinguishable from a small change in the rotational modulation in case of low data sampling and/or low data quality. At the same time, signals of less luminous flares would easily blend into the noise. Therefore, high precision space photometry from Kepler or TESS can be very useful in studying the optical signs of stellar activity in detail, including starspots and (super)flares, but it can also reveal such phenomena which are hardly or not observable from the ground, e.g., oscillations. Moreover, space instruments can provide continuous observations which are inevitably required to examine the temporal behaviour of complex (multiple) flare events or make up flare statistics for individual targets (e.g. Davenport 2016; Vida et al. 2017, 2019; Günther et al. 2020).

In our study we analyse the flaring activity of a target from the Kepler Input Catalogue under entry-name KIC 2852961 (2MASS J19261136+3803107, TIC 137220334) using Kepler and TESS observations. The star was listed in the ASAS catalogue of variable stars in the Kepler field of view (Pigulski et al. 2009) with 35.58 d rotational period, derived using 83 and 100 data points obtained in V and I colours, respectively, between May 28, 2006 and January 16, 2008. Figure 1 shows archival photometry from the Hungarian-made Automated Telescope Network (HATNet, Bakos et al. 2004) with 4475 datapoints in I_c colour collected during the observing season in 2006 (205 days). The folded light curve underneath, assuming P_{phot} = 34.27 d period, supports that the photometric period of ≃35 days is indeed due to rotation. Over and above, the shape of the slowly changing light curve is typical of spotted stars. From a little earlier period, in the 2003 HATNet dataset we found a large flare with an amplitude of about 0.08 mag in the infrared, i.e., well above the noise limit of ≃0.01 mag, unfortunately with sparse coverage of the decay phase; see Fig. 2. Note that observing such an event from the ground is just the matter of blind luck.

According to the NASA Exoplanet Archive[1], the low surface gravity of log g = 2.919, a surface temperature of 4722 K and a radius of 5.5 R_☉ together with the ≃35 d rotation period are all consistent with the preconception that KIC 2852961 is a late G-early K giant. The Kepler time series of our target were examined first by an automated Fourier-decomposition in Debosscher et al. (2011), who found signatures of rotational modulation.

with other non-classified signs of variability, however, the presumed eclipsing binary nature was not confirmed. In turn, based on new high-resolution spectroscopic data KIC 2852961 has recently been categorized as a single-lined spectroscopic binary (SB1), but without more details (Gaulme et al. 2020). Our star is included in Balona (2015) see Table 2. in that paper) as a rotational variable, but with a spurious period as the short-cadence Kepler data did not cover the entire rotation. In the short-cadence data Balona et al. (2015) searched for quasi-periodic pulsations induced by flares and found, that KIC 2852961 indeed showed distinct “bumps” in the flare decay branches, which might be flare loop oscillations and unlikely the signs of induced global acoustic oscillation.

In this study we use all the available Kepler and TESS light curves of KIC 2852961 in order to search for stellar flares and study their occurrence rate, which is the only study of its kind for a flaring giant star so far. The paper is organized as follows. In Sect. 2 our new spectroscopic observations are presented and analysed. In Sect. 3 we revise the stellar parameters of KIC 2852961. In Sect. 4 we give a summary of the Kepler and TESS observations, while in Sect. 5 the applied data processing methods are described. The results are presented in Sections 6–8 and discussed in Sect. 9. Finally, a short summary with conclusion is given in Sect. 10.

2. Mid-resolution spectroscopic observations and data analysis

New mid-resolution spectroscopic observations were taken between 04–08 April and 01–03 May, 2020 by the 1-m RCC telescope of Konkoly Observatory, located at Pískéstető Mountain Station, Hungary, equipped with a R=21000 échelle spectrograph. Altogether 27 spectra were collected with 2-5 exposures per day, depending on weather conditions. Circadian exposures
were combined to get eight combined spectra with total exposures between 1-3 hours, yielding signal-to-noise ratios larger than 40 for each. The spectra were reduced using standard IRAF\footnote{https://iraf.net} echelle reduction tasks. Wavelength calibration was done using ThAr calibration lamps. The observational log is given in Table\ref{tab:obslog}.

Radial velocity measurement were done in respect to the radial velocity standard HD 159222 (Soubiran et al. 2018). The temporal variation of the radial velocity of KIC 2852961 is plotted in Fig.\ref{fig:rv}. Despite the different weather conditions which are reflected by the size of the error bars, the plot clearly shows that the radial velocity significantly decreased from $\approx 25\, \text{km}\cdot\text{s}^{-1}$ in early April to $\approx 11\, \text{km}\cdot\text{s}^{-1}$ in the beginning of May, i.e., during about 25 days. This change could indeed be the sign of orbital motion, in line with the SB1 nature suggested by Gaulme et al. (2020), but further observations are necessary to cover the full orbit.

Three of the best quality combined spectra were used to estimate the rotational broadening of the spectral lines with spectral synthesis. We apply the spectral synthesis code SME (Spectroscopy Made Easy, Piskunov & Valenti 2017). Atomic spectral line data were taken from VALD database (Kupka et al. 1999) and MARCS atmospheric models (Gustafsson et al. 2008) were used. Keeping $T_{\text{eff}}$, log $g$ and [Fe/H] as free parameters the fits yielded $T_{\text{eff}}=4810\pm60\, \text{K}$, log $g=2.49\pm0.10\, \text{[cgs]}$ and [Fe/H]$=-0.25\pm0.10\, \text{cgs}$ with $\sin i=17.0\pm1.2\, \text{km}\cdot\text{s}^{-1}$. When $T_{\text{eff}}$, log $g$ and [Fe/H] are kept constant as 4722 K, 2.43 and $-0.08$, respectively (see Table\ref{tab:sme} in Sect.\ref{sect:rv}), the spectral fits yielded $\sin i=18.0\, \text{km}\cdot\text{s}^{-1}$ but with larger errorbars. Herewith, therefore, we accept $\sin i=17.5\, \text{km}\cdot\text{s}^{-1}$ but drawing attention to the fact that this result is preliminary due to the relatively low signal-to-noise ratio of the spectra and the smearing effect from the medium resolution.

### Table 1. Observing log of the spectroscopic data taken by the Hungarian 1-m RCC telescope.

| JD start | Date dd.mm.yyyy | Exposure time [s] | Number of exposures |
|---------|----------------|-------------------|--------------------|
| 2458944.4672 | 04.04.2020 | 3600 | 3 |
| 2458945.4630 | 05.04.2020 | 3600 | 3 |
| 2458946.5627 | 06.04.2020 | 1800 | 3 |
| 2458947.4635 | 07.04.2020 | 3600 | 3 |
| 2458948.5754 | 08.04.2020 | 1800 | 2 |
| 2458971.3811 | 01.05.2020 | 1800 | 5 |
| 2458972.4231 | 02.05.2020 | 3600 | 3 |
| 2458973.4620 | 03.05.2020 | 3600 | 3 |


\section{3. Revised stellar parameters of KIC 2852961}

The \textit{Gaia} DR-2 parallax of 1.2845$^{+0.0259}_{-0.0259}$ mas (Gaia Collaboration et al. 2018) with taking into account a mean offset of $-0.025\, \text{mas}$ (cf. Fig. 1 in Zinn et al. (2019) and their references) yields a distance of 813$^{+17}_{-17}$ pc for our target. According to the ASAS light curve (Pigulski et al. 2009) the brightest ever observed visual magnitude can be estimated as $V_{\text{max}}\approx 10^{+3.0}$.

This is consistent with the above mentioned distance and an interstellar extinction of $A_V=0.264$ from 2MASS (Skrutskie et al. 2006) gives an absolute visual magnitude of $M_V=-0.046$. The effective temperature $T_{\text{eff}}=4722\, \text{K}$ from the \textit{Kepler Input Catalogue} (Kepler Mission Team 2009) which is practically the same as 4739$^{+49}_{-44}$ K from \textit{Gaia DR-2} (Flower 1996). This yields a bolometric magnitude of $M_{\text{bol}}=-0.032\pm0.009$, convertible to $L = 76.5^{+6.3}_{-6.3}\, L_{\odot}$. Taking this luminosity value the Stefan-Boltzmann law would give $R=13.1^{+0.9}_{-0.9}\, R_{\odot}$. This new radius is more than two times bigger than the one listed in the NASA Exoplanet Archive, however, it is derived in a trustworthy way and it is in a better agreement with the radius of 10.64$ R_{\odot}$ given in \textit{Gaia DR-2} (Gaia Collaboration et al. 2018). The surface temperature and the derived luminosity are used to plot our target on the Hertzsprung–Russell (H-R) diagram in Fig.\ref{fig:hr}. Stellar evolution tracks are taken from Padova and Tri-
este Stellar Evolution Code (PARSEC, Bressan et al. 2012) for Z=0.01 ([M/H]=−0.175). From Fig. 3 we estimate a stellar mass of 1.7±0.2 $M_\odot$ for KIC 2852961 with an age of ~1.7 Gyr, i.e. around the red giant bump. We note however, that due to the uncertainty in metallicity the true errors should be ≈50% larger compared with those estimated from purely $T_{\text{eff}}$ and luminosity. The above mentioned mass and radius would yield a surface gravity of log $g=2.43±0.14$. Albeit this is smaller by ≈20% than the value of 2.919±0.145 given in the NASA Exoplanet Archive, it is more consistent with the revised atmospheric properties. Finally, taking $v sin i$ of 75 km/s obtained from spectral synthesis (see Sect. 4.1) with the maximum equatorial velocity of 50 km/s, we estimate a surface inclination. The most important stellar parameters of KIC 2852961 are listed in Table 2.

### Table 2. Revised astrophysical data of KIC 2852961

| Parameter                  | Value |
|----------------------------|-------|
| Spectral type              | G9-K0 III |
| Distance [pc]\(^{(a)}\)    | 813 ± 17 |
| $V_{\text{max}}$ [mag]\(^{(b)}\) | ≈10\(^{+0}_{-30}\) |
| $M_{\text{bol}}$ [mag]     | 0.032 ± 0.090 |
| Luminosity [$L_\odot$]     | 76.5\(^{+6.0}_{-5.3}\) |
| $T_{\text{eff}}$ [K]\(^{(c)}\) | 4722\(^{±56}\) |
| Radius [R$_\odot$]         | 13.1 ± 0.9 |
| Mass [$M_\odot$]           | 1.7 ± 0.3 |
| log $g$ [cgs]              | 4.5 ± 0.14 |
| Metallicity [Fe/H]\(^{(c)}\) | −0.08 ± 0.15 |
| $v sin i$ [km/s]\(^{(c)}\) | ≈17.5 |
| Inclination [°]            | 70 ± 10 |
| Photometric period [d]\(^{(c)}\) | ≈35.5 |

Notes. \(^{(a)}\) Taken from Gaia DR2. \(^{(b)}\) Taken from ASAS Archive. \(^{(c)}\) Computed by the Periodogram Tool of the NASA Exoplanet Archive.

### 5. Detecting flares in photometric data from space

We search for flares using an automated technique accompanied by visual inspection. For this, we apply an updated version of the flare detection pipeline from Gunther et al. (2020). We start from the detrended Kepler and TESS light curves and compute a Lomb-Scargle periodogram to identify (semi-)periodic modulation caused by stellar variability or rotation. The strongest periodic signal is removed using a spline with knots spaced at one tenth of the detected period. At the same time, we search for outliers by sigma clipping the data residuals, identifying and masking all outliers that are more than 3-$\sigma$ away. We repeat this entire process two more times or until no new periods are found, collecting a list of all outliers. These outliers are considered to be flare-like events if they contain a series of at least three consequent 3-$\sigma$ outlier points.

These candidates are then re-examined by eyeball to decide if they have a flare-like profile and can be declared a flare. To this end, the classical flare profile with a rapid rise followed by exponential decay branch helped in the verification. However, various doubtful cases were found at the low energy end, where quasi-oscillations, scatter and instrumental glitches either hampered the detection or caused false positives. At the end we confirmed 59 flare events in the Kepler time series (three of them were observed simultaneously in both short and long cadence data), while one single event was found in the much shorter TESS light curve.

### 6. Calculation of the flare energies

For each confirmed flare events we calculate flare energies in the following way. Let $I_0$ and $I_{0+f}$ be the intensity values (either bolometric or in a given bandpass) of the stellar surface at quiescent and flaring state, respectively. The flare energy relative to the star can be written as

$$e_f = \int_{t_1}^{t_2} \left( \frac{I_{0+f}(t)}{I_0} - 1 \right) dt,$$

where $t_1$ and $t_2$ are the start an the end points of the given flare event. The quiescent stellar flux is estimated using black body approximation, where Planck’s law gives the spectral radiance:

$$B(\lambda, T) = \frac{2h\lambda^2}{c^2} \frac{1}{\exp \left( \frac{c}{\lambda kT} \right) - 1}.$$

By integration over all solid angles of a hemisphere the spectral existance is $\pi B(\lambda, T)$, therefore the quiescent stellar luminosity through the Kepler filter would read

$$L_{\text{Kep}} = A_\star \int_{\lambda_1}^{\lambda_2} \pi B(\lambda, T) K(\lambda) d\lambda,$$

where $A_\star$ is the stellar surface while $K(\lambda)$ is the Kepler response function given between $\lambda_1$ and $\lambda_2$. At this point the total integrated flare energy through the Kepler filter is obtained by multiplying the relative flare energy by the quiescent stellar luminosity:

$$E_f = e_f L_{\text{Kep}}.$$

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\(^3\) [https://adina.feinstein.in/eleanor/](https://adina.feinstein.in/eleanor/)
Fig. 4. Long-cadence *Kepler* data of KIC 2852961. Note the rotational variability which is changing from one rotational cycle to the next, typical to stars with constantly renewing spotted surface. Several flare events are also present including really big ones.

Taking $R$ and $T_{\text{eff}}$ from Table 2, the quiescent stellar luminosity through the *Kepler* filter is $L_{\star,\text{Kep}} = 7.2 \times 10^{34}$ erg s$^{-1}$. (In comparison, the total bolometric luminosity from the Stefan-Boltzmann law is $L_\star = 2.85 \times 10^{35}$ erg s$^{-1}$.) The calculated $E_f$ flare energies with the corresponding $T_{\text{peak}}$ peak times and $\Delta t$ durations are listed in Table 3, together with the equivalent flare duration ($t_{\text{eq}}$) values. Note, that this latter is identical with $\epsilon_f$ from Eq. 1, since it is basically the time interval in which the star would radiate as much energy as the given flare itself, that is

$$t_{\text{eq}} \equiv \epsilon_f = \frac{E_f}{L_{\star,\text{Kep}}}.$$  

(5)

In Quarter 4 *Kepler* season, where both low and short cadence data are available, the calculations are performed for three confirmed flare events detected simultaneously in both datasets. The derived corresponding flare energies (see the 13–15th rows in Table 3) are quite close to each other, differing by 1–6% only. Therefore we estimate that the uncertainty of our flare energy calculations is within $\pm$10%.

The calculations above are repeated for the *TESS* flare but using the *TESS* transmission function instead; for the results see Table 4. We note that since $t_{\text{eq},\text{TESS}}$ and $E_{f,\text{TESS}}$ values in Table 4 are calculated using a different filter function, therefore they cannot be compared directly to the respective values of the *Kepler* flares in Table 3.

Among the flare events listed in Tables 3 and 4, the shortest ones last approximately 5 hours, while the longest one reached...
a length of two days, which is extremely long. The respective integrated energy values range between 10^{35} and 10^{38} ergs, i.e. they span over three orders of magnitude. In our case few times 10^{35} erg should be regarded as the detection limit due to data noise and other reasons (e.g., quasi-oscillations which slightly vary the overall brightness on a timescale of few hours). On the high end of the energy range some of the events show quite unusual structure. Such an event can be the result of multiple (regular or irregular) flare eruptions emerging at the same time, either in physical connection or independently by coincidence, however other (still unknown) mechanisms should also be considered; for possible alternatives see Sect. 9.

| $T_{\text{peak}}$ | $\Delta t$ | $t_{\text{eq}}$ | $E_f$ | $E_{f,\text{SC}}$ |
|-------------------|-----------|---------------|------|----------------|
| 163.329           | 33.60     | 936.879       | 6.74e+37 |                |
| 194.634           | 36.00     | 3157.145      | 2.237e+38 |               |
| 254.116           | 37.92     | 3330.501      | 2.398e+38 |               |
| 293.142           | 6.24      | 56.023        | 4.03e+36  |               |
| 314.923           | 26.40     | 216.666       | 1.56e+37  |               |
| 317.620           | 48.00     | 960.905       | 6.91e+37  |               |
| 332.659           | 31.20     | 336.170       | 2.42e+37  |               |
| 342.548           | 39.60     | 847.920       | 1.06e+37  |               |
| 344.367           | 9.60      | 18.327        | 1.32e+36  |               |
| 355.155           | 24.00     | 1023.951      | 7.37e+36  |               |
| 376.242           | 18.72     | 222.661       | 1.60e+36  |               |
| 382.290           | 29.76     | 1261.709      | 9.08e+35  |               |
| 405.156           | 27.12     | 328.035       | 2.36e+37  | 2.500e+37      |
| 407.281           | 15.84     | 875.386       | 6.30e+37  | 6.354e+37      |
| 408.057           | 27.36     | 822.838       | 5.92e+35  | 5.562e+37      |
| 417.212           | 19.20     | 1060.302      | 7.63e+36  |               |
| 430.330           | 22.08     | 367.232       | 2.64e+37  |               |
| 445.779           | 31.20     | 690.827       | 4.97e+37  |               |
| 448.946           | 24.00     | 393.929       | 2.83e+37  |               |
| 460.144           | 30.00     | 459.364       | 3.30e+36  |               |
| 471.506           | 21.60     | 1146.975      | 8.25e+37  |               |
| 479.230           | 14.88     | 80.285        | 5.78e+36  |               |
| 481.968           | 18.72     | 60.677        | 4.36e+36  |               |
| 491.634           | 7.92      | 66.901        | 4.81e+36  |               |
| 504.876           | 20.40     | 743.118       | 5.35e+37  |               |
| 518.015           | 16.80     | 1633.223      | 1.17e+38  |               |
| 531.154           | 6.72      | 35.933        | 2.58e+36  |               |
| 536.794           | 23.28     | 167.759       | 1.20e+37  |               |
| 542.495           | 22.80     | 736.110       | 5.30e+36  |               |
| 549.627           | 16.08     | 75.842        | 5.46e+36  |               |
| 556.288           | 28.80     | 1259.140      | 9.06e+37  |               |
| 588.001           | 25.20     | 699.830       | 5.03e+39  |               |
| 609.661           | 8.88      | 42.707        | 3.07e+36  |               |
| 612.726           | 32.88     | 773.672       | 5.57e+37  |               |
| 640.719           | 34.56     | 498.456       | 3.58e+37  |               |
| 646.869           | 13.20     | 82.132        | 5.91e+36  |               |
| 664.053           | 20.40     | 154.273       | 1.11e+37  |               |
| 672.839           | 14.40     | 228.669       | 1.64e+37  |               |
| 678.192           | 34.80     | 914.100       | 6.58e+37  |               |
| 774.105           | 21.60     | 269.828       | 1.94e+37  |               |
| 785.854           | 8.40      | 33.105        | 2.39e+36  |               |
| 787.489           | 7.44      | 16.188        | 1.16e+36  |               |
| 902.126           | 28.80     | 866.239       | 6.23e+37  |               |
| 902.923           | 5.28      | 10.871        | 7.82e+35  |               |
| 903.638           | 8.40      | 13.254        | 9.54e+35  |               |
| 908.890           | 6.96      | 29.748        | 2.14e+36  |               |
| 982.104           | 13.68     | 180.127       | 1.29e+37  |               |
| 1036.700          | 31.20     | 354.456       | 2.55e+37  |               |
| 1090.908          | 12.48     | 182.304       | 1.31e+37  |               |
| 1140.459          | 11.28     | 144.011       | 1.03e+37  |               |
| 1156.172          | 6.96      | 79.607        | 5.73e+36  |               |
| 1191.687          | 10.32     | 77.439        | 5.57e+36  |               |
| 1216.617          | 26.40     | 1312.973      | 9.45e+37  |               |
| 1330.395          | 23.52     | 1412.387      | 1.01e+38  |               |
| 1381.805          | 14.16     | 163.963       | 1.18e+37  |               |
| 1461.451          | 27.60     | 2501.156      | 1.80e+38  |               |
| 1472.914          | 22.32     | 321.986       | 2.31e+37  |               |
| 1566.071          | 5.28      | 7.629         | 5.49e+35  |               |
| 1571.793          | 32.40     | 1564.891      | 1.127e+38 |               |

From the list of flares in Table 3 we show two examples in Fig. 7, one with a complex structure and another one with a regular shape. We note that complex events similar to the plotted one might be the superimposition of a couple of simultaneous flares. Nevertheless, in our analysis such a complex flare is regarded as one single event, because in most cases it is hardly possible...
to differentiate a real complex event from a series of individual flares overlapping each other in time. On the other hand, it is very likely, that such simultaneous flare events are physically connected by sharing the same active region and maybe triggering each other as well (Lippiello et al. 2008), i.e., releasing magnetic energy from the same resource, therefore it is reasonable to handle them as one event. As a third example, in Fig. 9 we show the only flare detected in the TESS light curve (see Table 4), having a regular shape and lasting almost forty hours. The emitted energy of $\approx 10^{38}$ erg in the TESS bandpass (visible-near infrared spectrum) classifies it as one of the most powerful superflares of KIC 2852961 (cf. Table 5).

7. The cumulative flare frequency distribution

In order to investigate the dependence of flare occurrence on flare energy we follow the method introduced by Gershberg (1972), who found that cumulative flare frequency distribution (hereafter FFD) for flare stars tended to follow a power law (see also Lacy et al. 1976). According to that, the $\Delta N(E)$ number of flares in the energy range $E + \Delta E$ per unit time (days) can be written as

$$\Delta N(E) \propto E^{-\alpha} \Delta E.$$  

Rewriting in a differential form and integrating between $E$ and $E_{\text{max}}$ (i.e., the cutoff energy) one gets that the $\nu(E)$ cumulative number of flares with energy values larger than or equal to $E$ is

$$\nu(E) = c_1 \log E^{-1} + 1,$$  

where $c_1$ is a constant number. In logarithmic form it converts to

$$\log \nu(E) = c_2 + \beta \log E,$$  

i.e., a linear function between $\log \nu$ and $\log E$, where $c_2$ and $\beta = -\alpha + 1$ are constant numbers of the linear function, that is the intercept and the slope $1 - \alpha$, respectively.

It has been learned that the low energy turnover of the flare frequency distribution is most probably the result of the detection threshold (cf. e.g. Hawley et al. 2014), i.e. the low signal-to-noise ratio of small flares. Therefore we ran flare injection-recovery tests using the code allesfitter (Günther & Daylan 2019, 2020) to map out the detection bias in the low energy regime. First we set a suitable grid of artificial flares over the FWHMs and amplitudes of the flares, since these two properties feature the relative flare energy. The FWHM-amplitude grid was chosen to cover the relative flare energy range between $\log E = 0.0864-86.4$ sec, convertible to $\log E = 33.78-36.78$ [erg] total logarithmic flare energy (see Eq. 6). To make up the model flare light curves allesfitter adopts the empirical flare template described in Davenport et al. (2014).

The artificial flares were injected into the original Kepler light curve and then the flare detection algorithm (described in Sect. 5) was applied to recover them, this way characterizing statistically the recovery rate. The resulting injection-recovery plot is seen in Fig. 9 where blue gradient is used to visualize the recovery rate as the function of FWHM and amplitude (the darker the shade the lower the recovery rate). From the test we estimate a detection limit $t_{\text{det}}$ between 5-10 sec, in agreement with the results in Table 3. Towards higher FWHM values and amplitudes (i.e., higher energies) the recovery rate increases until the upper right corner of the grid, where the recovery rate virtually reaches $\approx 100\%$. From the recovery rates we derive correction factors (multiplicative inverses) to estimate the real flare numbers at the low energy range. These estimations are used to plot the detection bias-corrected cumulative flare frequency diagram.

The log-log representation of the flare frequency distribution diagram is shown in Fig. 10. At low energy the deviation from linear is nicely reduced compared to the grey dots which indicate the original (uncorrected) frequencies. But more markedly, having a breakpoint at around $E \geq 5 \times 10^{37}$ erg the distribution deviates from linear exhibiting a slight slope in the low energy regime and a much steeper part at the high energy end. Fitting the lower energy range (see the green line in Fig. 10) yields $\alpha = 1.29 \pm 0.02$. (We note that a fit to the uncorrected distribution over the same energy range would yield $\alpha = 1.21 \pm 0.02$.) Applying another fit to the high energy range above the break-

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Fig. 9. Result of the injection-recovery test. Each circle on the plot represents a given model flare characterized by its FWHM and amplitude. The recovery rate of the model flares is represented by a blue gradient bar where the darker the shade the lower the recovery rate. The energy range in total logarithmic flare energy extends from $\log E = 33.78$ [erg] up to $36.78$ [erg] where the recovery rate virtually reaches $100\%$.

Fig. 10. Detection bias-corrected cumulative flare-frequency diagram for KIC 2852961. The detection-biased original datapoints are plotted in grey color, above them are the corrected points in blue. The fit to the lower energy range below the breakpoint (green line) yields $\alpha = 1.29 \pm 0.02$ parameter, while the fit for the high energy range above the breakpoint (orange line) gives $\alpha = 2.84 \pm 0.06$. 

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point at $E \geq 5 \times 10^{37}$ erg gives $\alpha = 2.84 \pm 0.06$ (see the orange line in Fig. 10). This latter is significantly higher than the fit to the low energy part and higher than that usually derived for flaring dwarf stars (e.g., Howard et al. 2018; Paudel et al. 2018; Lim et al. 2019; Yang & Liu 2019, etc.). For further discussions on the broken flare energy distribution diagram see Sect. 9.2.

8. Correlation between spot modulation and flares

The light curve of KIC 2852961 in Fig. 4 shows significant change in the amplitude variation and the temporal distribution of flare occurrences during the whole mission. It is clearly seen that in the first third of the mission KIC 2852961 performed large amplitude rotational modulation with a lot of energetic flares; in the middle of the term the amplitude was getting smaller and the flares were getting less powerful and occurred less frequently; at the end of the term the amplitude increased again together with the average flare energies, although the flare frequency did not change much during the second half of the observing term. To quantify this observation, in Fig. 11 we plot the simple moving average of the overall amplitude change of the light curve cleaned from flares (top panel) together with the total flare energy within the same boxcar, which was set to be $3P_{\text{rot}}$ (bottom panel). In the lower edge of the bottom panel we mark the individual flare events by red ticks. The plot indicates that there is indeed a connection between the rotation amplitude (as an indicator of magnetic activity) and the overall magnetic energy released by flares. Especially interesting is the second half of the observing term starting with small amplitudes at BJD=800 (+2454833) with a few smaller flares. After a few rotation periods, at around BJD=900 the amplitude started to increase significantly, just like the flare energies. This pattern is even more apparent from BJD=1300, where the amplitude of the rotational modulation increases more rapidly which coincides with the overall flare energy increase (without the increase of the average flare count). This result suggests a general scaling effect behind the production flares in the sense that there are more and/or more energetic flares when having more/larger active regions on the stellar surface and the flare activity is lower when there are less/smaller active regions. In Sect. 9.4 we give a few more words on this topic.

9. Discussions

9.1. On the stellar evolution, rotation and differential rotation

The revised stellar parameters of KIC 2852961 listed in Table 2 are in agreement with the new Gaia DR-2 observations and are more consistent with each other. The mass of about 1.7 $M_{\odot}$ is considerably higher than the formerly suggested mass of $\approx 0.9M_{\odot}$ (NASA Exoplanet Archive). The higher mass we find is suggestive of a faster evolution or younger age of $\approx 1.7$ Gyr as well (which is tightly interrelated with mass). Taking the relation $t_{\text{MS}} \propto M^{-2.5}$ between the main sequence period and mass with $0.9M_{\odot}$ instead of 1.7 $M_{\odot}$ and supposing no significant mass loss at the red giant branch (cf. e.g., McDonald & Zijlstra 2015) would mean a much slower evolution on the main sequence. The mass-radius relation (see e.g., Mihalas & Binney 1981; Demircan & Kahraman 1991) one can estimate $R_{\text{MS}} \approx 2.0 R_{\odot}$ for the main sequence, i.e., a typical A5-F0 type progenitor (cf. Boyajian et al. 2012, 2013). Assuming that our SB1 target (cf. Gaulme et al. 2020) has a distant and/or too low mass companion with having insignificant influence and the angular momentum is conserved over the red giant branch, applying the relation $P_{\text{rot}} \propto R^2$ will give $P_{\text{rot,MS}}$ of $\approx 1$ d period at the end of the main sequence. This rotation rate is high, but not unusual for an effectively single A5-F0 star just leaving the main sequence, since in stars with $>1.3 M_{\odot}$ mass the lack of deep convective envelope does not enable to generate enough strong magnetic fields to maintain effective magnetic braking over the main-sequence (van Saders & Pinsonneault 2013). Still, other mechanisms could also be considered to spin up the surface of an evolved star on the red giant branch. A certain fraction of red giants have undergone such spin up phases (e.g., Carlobreguet al. 2011; Ceillier et al. 2017), which may involve mixing processes (Simon & Drake e.g., 1989 but see also Kriskovics et al. 2014; Kovári et al. 2017b), planet engulfment (Sies & Livio 1999; Kovári et al. 2016), binary mergers (Webbink 1976; Strassmeier et al. 1998) or other, less known mechanisms. However, the lack of systematic radial velocity measurements does not enable to know whether KIC 2852961 is a member of a wide binary system or rather a close binary. In the latter case the stellar rotation is probably synchronized to the orbital motion which would evidently account for the 35.5 day period.

Interpreting the multiple peaked power spectrum in Fig. 6 together with the different photometric periods obtained for different datasets (see Sect. 1) as the signs of surface differential rotation, we give a low end estimate for the surface shear parameter $\Delta P/P$ to be $\approx 0.1$. This value agrees with the result in Kovári et al. (2017a) see their Fig. 1), where authors predict $\approx 0.17$ for a single giant rotating at a similar rate, based on an empirical relationship
between rotation and differential rotation. From photometric observations only, however, usually it is not evident to determine, whether the differential rotation is solar-type (i.e., when the angular velocity has its maximum at the equator and decreases with latitude) or oppositely, antisolar (but see Reinhold & Arlt 2015).

9.2. On the cumulative flare frequency diagram

With the detection bias-correction even the broken flare energy distribution is more apparent. Such a broken distribution has already been observed in a few dwarf stars (Shakhovskaia 1989; Paudel et al. 2018) including the Sun (Kasinsky & Sotnicova 2003). Mullan & Paudel (2018) interpreted this feature as energy release from twisted magnetic loops at different energies: below and above a critical energy when the loop size becomes higher than the local scale height depending on the local field strength and density. Below and above the critical energy the power law slopes are different and the breakpoint is at the critical energy. This critical energy is different from star to star, and the flare energy distribution does not necessarily contain it, therefore - apart from the natural undersampling at low energies - a single power law can also describe flare energy distributions of many stars. This scenario of Mullan & Paudel (2018) was developed for dwarf stars taking into account only simple flares. Specifically, Shibayama et al. (2013) derived \( \alpha = 2.0 - 2.2 \) power-law indices for Kepler G-dwarf superflare stars while \( \alpha=1.53 \) for the “normal” solar flares. Mullan & Paudel (2018) suggested a critical energy around \( 10^{32} - 10^{33} \text{erg} \) for solar-like stars. Our result of KIC2852961 is \( \alpha = 2.84 \) and 1.29 for the superflare and normal flare part of the frequency distribution, respectively, with the critical energy being about \( 10^{37.6} \text{erg} \). The big difference between the critical energies and the slopes of the distributions are very probably due to the differences between the atmospheric parameters (e.g., \( \log g \), density) of dwarf and giant stars and the characteristic magnetic field strengths. Anyhow, the aforesaid interpretation of the broken distribution supports the idea that flares/superflares in solar-type dwarf stars and in flaring giants have common origin but reveal themselves on different energy scales.

But further explanations may also arise. Wheatland (2010) studied a sample of small X-ray flares observed by GOES satellite, all erupted form one active region on the Sun. In the flare frequency distribution they found a departure from the standard power-law (1.88 \( \pm 0.12 \)) which was interpreted as a possible result of finite magnetic free energy for flaring. Lin et al. (2019) discussed three possible reasons behind the broken power-laws: i) undetected multiplicity of flaring stars with different flare frequencies superimposed; ii) flares can be produced by different active regions on the same star having different flare statistics; iii) a close-in planetary companion could trigger flares with a different mechanism adding events to the intrinsic flare distribution. Finally, the work by Yashiro et al. (2006) could bring an additional perspective regarding the different power-law indices: authors found that the power-law indices for solar flares without coronal mass ejections (CMEs) are steeper than those for flares with CMEs. This interpretation might also work for stellar flares, however, so far only a handful of stellar CMEs has been detected, all of them by spectroscopy (see the recent statistical study by Leitzinger et al. 2020 and their references). Accordingly, without spectroscopic observations it is not possible to draw such a distinction in our flare sample.

9.3. On the flare energy statistics

Comparing the flare energies of a mixed sample of flares observed on giant stars by Kepler (Yang & Liu 2019) against the flare energies of KIC 2852961 we find that KIC 2852961 flares are more powerful. Both the 35.503 mean and the 35.417 median of the \( \log E_f \) values in the cited sample of 6842 flares from giant stars are well below our values of 37.286 and 37.384, respectively. Nevertheless, our flare sample is statistically much smaller.

In the top panel of Fig. 12 the energy distribution functions of two superflaring stars are compared with that of our target. One of them, KIC 2968811 is a late-G giant with remarkably similar astrophysical parameters to KIC 2852961, except that it rotates two times faster, while the other one is a subgiant, otherwise with similar parameters as well (see Table 5). The three histograms are dissimilar because of their different energy ranges, but even more strikingly because, in contrast with the
other two stars where histograms are Poisson-like, the histogram for KIC 2852961 exhibit relatively more flares at the high energy end. Such an excess at high energies, however, could be a bias from accounting the complex (and so possibly simultaneous) flares as single ones. Therefore, we clean the flare sample for KIC 2852961 by excluding the complex events (27 of 59 in Table 5) to see the energy distribution of the regular flares separately. In the bottom panel of Fig. 12 the histogram of the fraction of regular flares (plotted in dark red) shows similar increase at high energies. This supports that the unlikeness of the histogram for KIC 2852961 is not simply an artifact; it seems as if KIC 2852961 may favor the production of superflares. But again, our sample of altogether 59 flares (with 27 regular shaped among them) is statistically scant, which should also be borne in mind.

9.4. On the scaling effect behind different flare statistics

Ilin et al. (2019) published average slopes of frequency distribution of flare stars in three open clusters (Pleiades, Praesepe and M67) of different ages (0.125, 0.63 and 4.3 Gyr, respectively) observed by Kepler. The power-law exponents were found not to change with age, and the same was found by Davenport et al. (2019), reflecting a probable universal flare producing mechanism, regardless of age (+metallicity, rotational evolution, etc.).

Balona (2015) studied Kepler flare stars of different luminosities and found that higher luminosity class stars, including giants, have generally higher energy flares. This finding (Balona 2015 see Fig. 10 in that paper) is attributed by the author to a scaling effect, i.e., in the larger active region of a larger star more energy can be stored from the same magnetic field strength. Another important finding of Balona (2015) is that stars with lower surface gravities have longer duration flares. Maehara et al. (2015) found that flare duration increases with flare energy, which can be explained by assuming that the time scale of flares emerging from the vicinity of starspots is determined by the characteristic reconnection time (Shibata & Magara 2011). Accordingly, the relationship between $\Delta t$ and $E_f$ for solar-type main sequence stars is expected to be $\Delta t \propto E_f^{1/3}$. For comparison, in Fig. 13 we plot $\log \Delta t$ vs. $\log E_f$ values for KIC 2852961. The dots are fitted by a power-law in the form of

$$\log \Delta t [\sec] = -7.3(\pm 1.0) + 0.33(\pm 0.03) \log E_f [\text{erg}].$$

We note that fitting either the regular flares (grey dots) only or the complex events (red dots) would yield $0.29(\pm 0.03$ and $0.36(\pm 0.04$ slopes, respectively. However, due to small sample sizes, the difference is statistically not significant. The slope of $0.33(\pm 0.03$ in Fig. 13 is similar to the value of $0.39(\pm 0.02$ in Maehara et al. (2015) obtained for G-type main sequence stars, supporting the idea that the differences between flare energies are due to size effect (cf. Balona 2015). This scaling idea is echoed by the avalanche models for solar flares, which regard flares as avalanches of many small reconnection events (for an overview see Chardonneau et al. 2001). This statistical approach could consistently be extended to provide a common framework for solar flares and stellar superflares over many orders of magnitude in energy. Finally, we emphasize, that the result presented in Sect. 8 suggests a clear connection between the level of spot activity and the overall flare energy. This is concordant with the scaling idea by Balona (2015), i.e. when having larger active regions more magnetic energy can be stored and thus released by flares (but see also Lehtinen et al. 2020) for a common dynamo scaling in all late-type stars.

10. Summary and conclusion

In this paper the flare activity of the late G-early K giant KIC 2852961 were analyzed using the full Kepler data (Q0-Q17) and one TESS light curve (Sector 14 from July-August 2019) in order to study the flare occurrence and other signs of magnetic activity. Foremost, adopting the Gaia DR-2 parallax we revised the astrophysical data of the star and more reliable parameters were derived, in agreement with the position in the H-R diagram. We found altogether 59 flare events in the Kepler time series and another one in the much shorter TESS light curve. Logarithmic flare energies range between 35.74–38.38 [erg], i.e., almost three orders of magnitude, however, the detection cutoff at low energy end is very likely due to the noise limit. We derived a cumulative flare frequency distribution diagram which deviated from a simple power-law in the sense that different exponents were obtained for the lower and the higher energy ranges, having a breakpoint between them. We reviewed a couple of possible explanations to understand the broken power-law. Flare counts and total flare energies per unit time show temporal variations, which are related to the average light curve amplitude. A straightforward interpretation is that the higher the level of spot activity the

Table 5. Comparing stellar parameters of KIC 2852961 with those of two other superflaring Kepler stars (cf. Fig. 12, top panel).

| Parameter | KIC 2852961 | KIC 2968811 | KIC 9093349 |
|-----------|-------------|-------------|-------------|
| $P_{\text{rot}}$ [d] | 35.5        | 14.84       | 5.48        |
| $T_{\text{eff}}$ [K] | 4722$^{+77}_{-56}$ | 4697$^{+117}_{-105}$ | 5130$^{+154}_{-105}$ |
| $R$ [$R_\odot$] | 13.1 $\pm 0.9$ | 15.50$^{+3.49}_{-6.40}$ | 4.00$^{+1.136}_{-2.109}$ |
| $M$ [$M_\odot$] | 1.7 $\pm 0.3$ | 1.628$^{+0.190}_{-0.570}$ | 1.585$^{+0.213}_{-0.639}$ |
| $\log g$ [cgs] | 2.43 $\pm 0.14$ | 2.269$^{+0.300}_{-0.200}$ | 3.434$^{+0.497}_{-0.213}$ |

Notes. Rotation period, effective temperature, radius, mass and surface gravity of KIC 2968811 and KIC 9093349 are taken from NASA Exoplanet Archive.

Fig. 13. Flare duration vs. flare energy for KIC 2852961 in log-log interpretation. Grey dots are regular flares while red dots indicate the complex events. The fit supports a power-law relationship with $0.33(\pm 0.03$ exponent.
more the overall magnetic energy released by flares and/or superflares. This exciting result supports the assumption that differences in flare (superflare) energies of different luminosity class targets are very likely due to size effect.

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