

Kepler super-flare stars: what are they?

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ABSTRACT

The *Kepler* mission has led to the serendipitous discovery of a significant number of “super flares” – white light flares with energies between 10^{33} erg and 10^{36} erg – on solar-type stars. It has been speculated that these could be “freak” events that might happen on the Sun, too. We have started a programme to study the nature of the stars on which these super flares have been observed. Here we present high-resolution spectroscopy of 11 of these stars and discuss our results. We find that several of these stars are very young, fast-rotating stars where high levels of stellar activity can be expected, but for some other stars we do not find a straightforward explanation for the occurrence of super flares.

Key words. stars: activity – stars: chromospheres – stars: flare – stars: solar-type – stars: rotation – stars: atmospheres

1. Introduction

The NASA *Kepler* space observatory has collected high-precision photometric measurements at a cadence of 29.4 min for $\sim 156\,000$ stars (Jenkins et al. 2010). While the primary goal of the *Kepler* mission has been to detect extrasolar planets, the large amount of photometric data has enabled serendipitous observation of large numbers of rare yet highly energetic “super flares” on solar-type stars (Maehara et al. 2012; Shibayama et al. 2013).

The super flares detected by these authors are white-light flares with bolometric energies of $\geq 10^{33}$ erg that typically reach 0.1 to 1 per cent of the stellar luminosity, and they last for a few hours. For comparison, the largest known solar flare – the Carrington event on Sept. 1, 1859 (Carrington 1859) – had an estimated energy of the order of $\geq 10^{32}$ erg (Tsurutani et al. 2003).

It is intriguing that flares of such magnitude can occur on solar-type stars, in particular because some of these events took place on slowly rotating stars (>10 days rotation period). Maehara et al. (2012) find that the frequency of super flares on slow rotators is only 1/20 of that for fast rotators, so there is clearly a strong tendency towards fast-rotating, hence statistically young stars. Still, one may ask whether the Sun itself is also capable of producing such flares (albeit rarely) or whether the stars showing such events are in some way special. So far only a few spectroscopic studies of *Kepler* super-flare stars have been carried out. Notsu et al. (2013) have studied the G-type star KIC 6934317, which exhibits a low lithium abundance combined with fast rotation (though apparently observed nearly pole on). It has a high rate of super flares, but does not seem to be particularly young. Nogami et al. (2014) have studied the slowly rotating stars KIC 9766237 and KIC 9944137 (rotation periods 21.8 d and 25.3 d, respectively) and report that both stars are similar to the Sun with respect to metallicity, temperature, and surface gravity. They do not find any hint of binarity, although they cannot firmly rule out a low-mass companion.

We aim to study the nature of the stars on which super flares have been observed and have started a programme to carry out

high-resolution spectroscopic observations of selected stars from the list of Maehara et al. (2012). In particular, we are investigating whether these stars show other indicators that are usually associated with high levels of activity, such as fast rotation or high lithium $\lambda 6707$ equivalent width (EW), which indicate stellar youth, or rapid line shifts showing that the star is in a close binary system.

The paper is structured as follows. In Sect. 2 we describe the observations and data collected. Section 3 explains our general methods and results, and in Sect. 4 we discuss the individual stars of our sample.

2. Target selection and observations

Our programme started as a backup programme for the Calar Alto 2.2 m telescope with the CAFE spectrograph, which meant that the primary selection criteria was that the stars had to be bright enough for observations with a 2.2 m telescope and had to be observable at the time of the original run. Target stars were observed multiple times in order to detect eventual radial velocity variations caused by multiplicity. We aimed for a signal-to-noise ratio (S/N) of about 50 when choosing exposure times, but owing to bad weather we could not reach this goal for all observed stars.

The first observing run took place from Aug. 17 to Aug. 21, 2012 at the Calar Alto 2.2 m telescope with the CAFE echelle spectrograph ($R \approx 65\,000$, spectral range 390–960 nm, 88 orders). During the first three nights, the weather was poor, while the last two nights had very good weather conditions. Table 1 lists the stars observed in this run, along with stellar parameters from the literature. The values marked KIC are taken from Brown et al. (2011), the values marked SDSS are from Pinsonneault et al. (2012) derived with the SDSS method. Rotation periods were derived using the periodogram tool of the NASA exoplanet archive¹.

For KIC 11390058 some episodes of the light curve do not show a stable rotation pattern, as shown in Fig. 4. However,

¹ <http://exoplanetarchive.ipac.caltech.edu/index.html>

Table 1. Stars observed and their stellar parameters from the literature.

KIC	RA [h m s]	Dec [° ' "]	T_{eff} KIC [K]	$\log g$ KIC	T_{eff} SDSS [K]	P [days]
3626094	18 59 14.9	+38 45 46	5835	4.3	6156	0.72
4742436	19 21 49.5	+39 50 07	5628	4.2	5980	2.3
4831454	19 21 58.0	+39 59 54	5298	4.6	5536	5.2
7264976	19 02 36.1	+42 48 31	5184	4.1	5400	12.7
8479655	18 57 43.2	+44 35 55	5126	4.6	5415	19.3
9653110	19 33 48.3	+46 21 54	5223	4.4	5474	3.2
11073910	19 04 27.7	+48 36 55	5381	4.6	5640	5.5
11390058	18 56 45.9	+49 17 30	5785	4.3	6086	11.9
11610797	19 27 36.7	+49 40 14	5865	4.5	6090	1.6
11764567	19 30 33.6	+49 56 04	5238	4.4	5480	20.5
11972298	19 44 23.3	+50 22 12	5498	4.4	5741	15.5

Notes. KIC 9653110, KIC 11390058, and KIC 11972298 were observed in the 2013 run. Periods for KIC 11390058 and KIC 11972298 are from Maehara et al. (2012).

many light-curve intervals clearly yield a rotation period of approximately 12 days, and we use the value of 11.9 days given in the supplement of Maehara et al. (2012).

For KIC 11972298 some light curve intervals suggest a period of approx. eight days. However, this seems highly unlikely in view of all available Kepler quarters. As for KIC 11390058, many light curve intervals clearly indicate a rotation period of about 15 days, and again we use the Maehara et al. (2012) value of 15.5 days. We note that Shibayama et al. (2013) prefer the shorter period and list 7.7 days for this star.

We had a second observing run from May 28 to May 31, 2013. Unfortunately, the S/N of most spectra of this run turned out to be too low to perform our parameter analysis. The three stars with usable data are listed in Table 1. KIC 7264976 has been observed in 2012 and 2013, but the 2013 data only suffice to determine radial velocities. Data reduction was performed using standard IRAF² tasks for bias correction, flat fielding, order extraction, and wavelength calibration.

3. Results

3.1. Determination of stellar parameters

We determined the stellar parameters using two different methods. First, we utilised “spectroscopy made easy” (SME, Valenti & Piskunov 1996), and second we fitted PHOENIX model spectra (Husser 2013) to our observed spectra. For both methods we used averaged spectra of our objects to improve the S/N.

We based our SME fits on atomic data from VALD3³ (Kupka et al. 1999) and determined empirical oscillator strength corrections to improve agreement between the synthetic and observed spectrum of the Sun following the procedure described in Valenti & Fischer (1996). As model input to SME, we used Kurucz model atmospheres (Kurucz 1993). Furthermore, we set the micro turbulence velocity to 0.85 km s^{-1} and the macro turbulence to 3.0 km s^{-1} . The spectroscopic orders were fitted individually, and the low S/N regions at both ends of each order were clipped. Wavelength regions showing cosmetics were excluded from the analysis. In a first fitting step, we determined the

Table 2. Start and end wavelengths of the orders used for determining stellar parameters.

Start [Å]	End [Å]
5012	5066
5057	5111
5102	5157
5196	5251
5446	5504
5499	5558
5553	5612
5608	5668
5664	5724
5721	5782
6293	6361
6364	6432

radial velocity of each object. We then fitted 12 spectral orders independently with T_{eff} , $\log g$, and $v \sin i$ as free parameters for each order. The criteria for selecting those orders were high S/N, avoidance of eventual contamination by chromospheric emission, and avoidance of wavelength regions strongly affected by telluric lines. The wavelength ranges of these orders are listed in Table 2. For the three objects KIC 8479655, KIC 11073910, and KIC 3626094, we fitted all orders with $S/N > 10$ (a total number of 52 orders) to verify that the fitting process with only 12 orders gives parameters in agreement with fitting all usable orders. An example of the determined parameters for each order can be found in Fig. 1. Only for the stars KIC 11972298 and KIC 11390058 did we choose different orders because the low S/N made some of the orders unusable for the fitting. For each free parameter, we took the mean of this fitting process as the final stellar parameters and its standard deviation as a robust error estimate.

Furthermore, we conducted some upstream studies with SME to investigate how our fitting results were sensitive to different methods of analysis regarding the error estimation. For KIC 8479655, KIC 3626094, and KIC 11073910, we fitted our parameters T_{eff} , $\log g$, and $v \sin i$ using the same pair of four wavelength intervals as described in Valenti & Fischer (1996). Our results show that these methods are not more precise, and they lead to the same error range as the method described above. We also investigated how sensitively our determined parameters depend on (i) the radial velocity, which we varied within twice

² IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

³ <http://vald.inasan.ru/~vald3/php/vald.php?docpage=rationale.html>

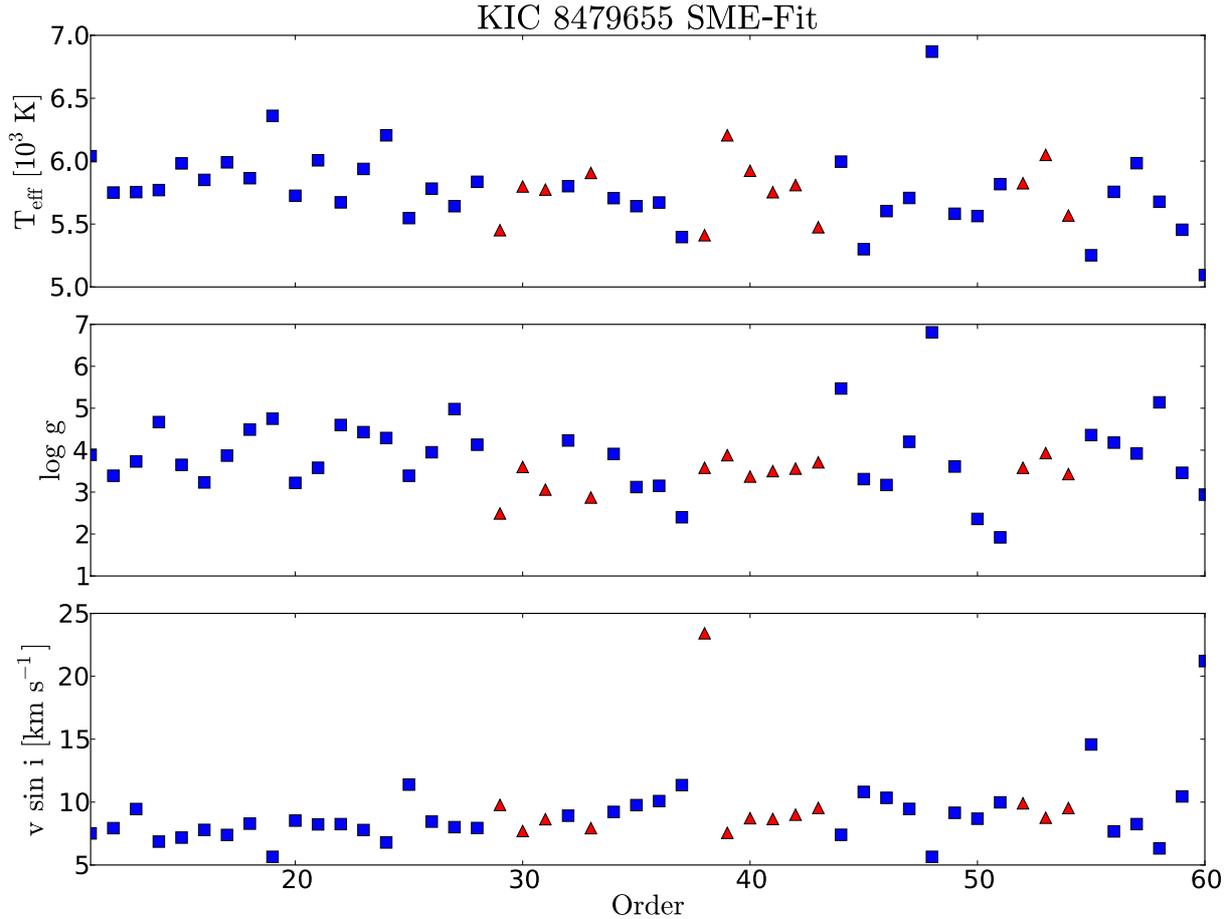


Fig. 1. Best fitting parameters for all orders for KIC 8479655. The orders marked with triangles are used for the fitting of the other objects.

Table 3. Stellar parameters determined with SME and PHOENIX.

KIC	S/N	v_r [km s ⁻¹]	PHX T_{eff} [K]	SME T_{eff} [K]	log g PHX	log g SME	$v \sin i$ PHX [km s ⁻¹]	$v \sin i$ SME [km s ⁻¹]
3626094	50	-46 ± 1	6000 ± 200	5900 ± 100	4.0 ± 0.5	4.2 ± 0.3	9 ± 3	6.1 ± 0.4
4742436	60	-55 ± 1	6100 ± 150	5945 ± 90	4.0 ± 0.5	4.3 ± 0.3	9 ± 3	7.0 ± 0.6
4831454	70	-25 ± 1	5600 ± 150	5530 ± 85	4.5 ± 0.5	4.6 ± 0.2	6 ± 3	5.5 ± 0.4
7264976A	50	-11 ± 2	5750 ± 150		5.0 ± 0.5		18 ± 5	
7264976B		-11 ± 2	5100 ± 200		5.0 ± 0.5		9 ± 3	
8479655	20	-35 ± 1	6200 ± 300	5670 ± 200	4.5 ± 0.5	3.7 ± 0.4	9 ± 3	9.0 ± 1.5
9653110	17	-35 ± 3	6000 ± 400	5700 ± 400	4.0 ± 0.5	4.5 ± 0.9	80 ± 10	87.0 ± 8.9
11073910	45	-1 ± 1	6500 ± 150	6750 ± 400	4.5 ± 0.5	4.8 ± 0.5	18 ± 3	11.2 ± 1.3
11390058	17	-23 ± 3	6000 ± 400	5740 ± 300	4.5 ± 0.5	4.5 ± 0.8	12 ± 3	9.9 ± 3.9
11610797	50	-14 ± 3	5900 ± 200	5650 ± 150	4.0 ± 0.5	4.1 ± 0.6	24 ± 3	28.4 ± 1.1
11764567	17	-1 ± 3	6100 ± 300	5640 ± 240	4.5 ± 0.5	3.5 ± 0.8	21 ± 3	19.3 ± 2.5
11972298	17	12 ± 3	6100 ± 400	5500 ± 400	4.0 ± 0.5	3.7 ± 1.0	21 ± 6	17.6 ± 10.2

the range of our error estimates; and (ii) variations in the macro turbulence velocity. The latter is important, since we did not re-fit the stellar parameters with the correct macro turbulence velocity after obtaining the effective temperature. Both variations in the radial velocity and the macro turbulence velocity had a very weak effect on the derived stellar parameters, which was negligible in comparison to our error estimates. We repeated the analysis with $[M/H]$ as additional free parameter. The metallicity analysis was only possible for the three objects with highest S/N and slowest rotation.

For the PHOENIX model spectra fits, we used a grid with T_{eff} ranging from 5000 to 6600 K in steps of 100 K and

log g ranging from 4.0 to 5.5 in steps of 0.5. During the χ^2 -fitting process, we rotationally broadened the model spectra with $v \sin i$ ranging from 3 to 27 km s⁻¹ in steps of 3 km s⁻¹, except for KIC 9653110, where we varied $v \sin i$ from 30 to 100 km s⁻¹ in steps of 10 km s⁻¹. We did not fit the metallicity with PHOENIX, but assumed solar metallicity. We used 60 of the 80 orders for the fitting process and again determined the final stellar parameters as the mean and its standard deviation.

The stellar parameters determined using both methods can be found in Table 3. Heliocentric velocity corrections were computed using the IRAF “rvcorr” task. The parameters found by the SME fit with metallicity as additional free parameter can

Table 4. Stellar parameters determined with SME including the metallicity as free parameter.

KIC	T_{eff} [K]	$\log g$	$v \sin i$ [km s ⁻¹]	[M/H]
3626094	5950 ± 200	4.3 ± 0.4	5.8 ± 0.3	-0.01 ± 0.13
4742436	5850 ± 200	4.1 ± 0.4	6.7 ± 0.5	-0.09 ± 0.18
4831454	5610 ± 120	4.8 ± 0.2	5.3 ± 0.4	0.03 ± 0.17

be found in Table 4. For the binary star KIC 7264976, we used only PHOENIX spectra to determine the stellar parameters of both components, which are shifted relatively to each other by 12 km s⁻¹, since SME is not suited to fitting binary stars.

Generally, the PHOENIX fitting method and SME give similar results, which usually agree within their respective errors. However, the PHOENIX fits systematically yield slightly higher effective temperatures.

3.2. Stellar activity

We tried to infer the activity level of the stars from several strong chromospheric lines. We compared the best-fitting PHOENIX spectrum to the observed spectrum to find excess line emission or absorption for the strongest chromospheric lines in our stellar spectra, namely H α , Na I D, Ca II at 8498, 8542, 8662 Å, H β , H γ , and H δ .

The best line indicators are H α and the Ca II infrared triplet, since these are strong, unblended lines with a well defined continuum level. The Na I D lines are significantly affected by the presence of strong telluric lines in their vicinity, and the higher Balmer lines suffer from both the lack of a well defined continuum and the declining flux in the blue region of the spectrum.

We also compared these chromospheric lines to an observed spectrum of an inactive G0 dwarf star, HD 115383 (59 Vir), from the UVES spectral atlas⁴. This yielded results that are similar to the comparison to the best-fitting PHOENIX spectrum. As an example of chromospheric activity, in Fig. 2 we show the H α line for the stars in our sample, as well as for the reference star HD 115383. The reference star is not rotationally broadened, since for the H α line, rotationally broadening plays no significant role in the velocity regime considered here.

In Sect. 4 we note for each star which chromospheric lines are filled in. We measured absolute H α EW, but these are hampered by the fact that in many cases, the Voigt profile used results in a poor fit. We therefore computed the EW by integrating the residual line after subtracting a quiescent reference star, again using the spectrum of HD 115383 for the latter. We estimate our errors to be about 20–30 mÅ for the stars with S/N of 45 and higher, and about 50 mÅ for the low S/N stars because of the larger uncertainty in the normalisation. For the EW computation, the effect of cosmics has been removed by replacing them with the mean values of neighbouring pixels, but to show their location we did not remove them in Fig. 2.

This method has also been used by Froehlich et al. (2012) and Soderblom et al. (1993b), who give a subtracted EW(H α) between 100 and 500 mÅ for early G stars at the age of the Pleiades. Our EW values, given in in Table 5, match these values, with the notable exception of KIC 3626094.

Table 5. Measured EW for individual lines.

KIC	EW_{Li} [mÅ]	EW_{Fe} [mÅ]	Subtracted
			H α EW [mÅ]
3626094	56	4	50
4742436	67	8	120
4831454	154	13	220
7264976	76	16	330
8479655	–	17	430
9653110	550
11073910	66	12	460
11390058	93	4	340
11610797	210	4	310
11764567	–	15	230
11972298	430

Two of the stars (KIC 11610797 and KIC 8479655) show asymmetries in their H α lines that significantly affect the EW(H α) measurements. We discuss this in more detail in Sect. 4.

3.3. Lithium

Lithium is rapidly burned at the bottom of the convective zone in low-mass stars, and therefore its line at 6707 Å is often used as an age indicator. While there is substantial scatter at a given T_{eff} even within open clusters, that is to say among coeval stars (e.g. Soderblom et al. 1993a), this scatter occurs downward from an upper limit in the ($EW_{\text{LiI}} - T_{\text{eff}}$) diagram. In particular, the upper limit for the Pleiades, which is defined well by a large number of measurements, is a robust benchmark in the sense that no older stars are located *above* it (Wichmann 2000). The Pleiades have an age of about 125 Myr (Tognelli et al. 2012).

The EW of Li I at 6707 Å for our programme stars has been measured with IRAF using the SPLIT task. For each star, three independent measurements have been averaged to form the final result. The main source of error is the estimation of the local (pseudo-)continuum, which leads to an rms error of ≈ 5 mÅ. The spectral region around the Li I 6707.44 Å line is shown in Fig. 3, and the measured results are given in Table 5, along with the *expected* contribution from the blend with the Fe I 6707.44 Å line (Favata et al. 1993, Fig. 1).

3.4. Kepler light curves

In Fig. 4 we show the *Kepler* light curves of our target stars as taken from the NASA exoplanet archive⁵. We used the Lomb-Scargie periodogram analysis provided as a service by the NASA exoplanet archive to search for periods in the light curves. Generally all stars show more than one significant peak in the periodogram mostly due to aliasing.

The light curve patterns of the stars in our sample can be divided into three groups. The first and largest group shows a well defined periodic behaviour, although there seem to be secondary maxima, some of which are drifting slowly with respect to the main maximum (KIC 3626094, KIC 4831454, KIC 7264976, KIC 8479655, and KIC 11764567). The second group of light curve patterns is similar to the first but additionally shows a distinct beating pattern in its light curve (KIC 9653110, KIC 4742436, and KIC 11610797). The beat period is not well

⁴ The UVES spectral atlas is available at https://www.eso.org/sci/observing/tools/uvespop/field_stars_uptonow.html

⁵ The web page can be found under: <http://exoplanetarchive.ipac.caltech.edu/index.html>

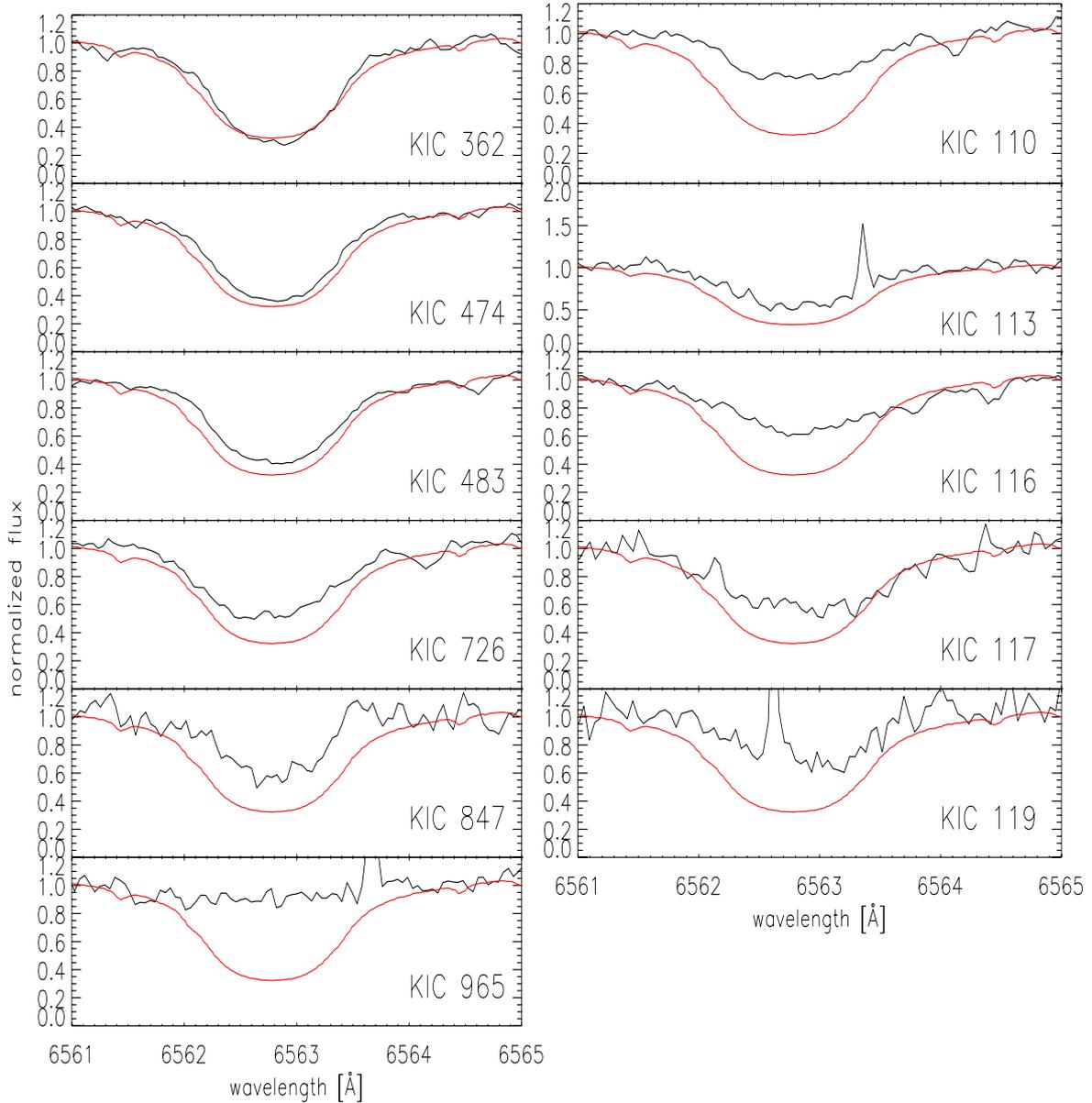


Fig. 2. $H\alpha$ line for the sample stars and the inactive star HD 115383. The asymmetries in the red wing of the line in KIC 8479655 (emission feature at about 6563.5 Å) and KIC 11610797 (broad additional absorption feature between about 6563 and 6564.5 Å) are clearly visible. KIC 9653110 and KIC 11972298 both have a cosmic in the $H\alpha$ line.

defined for any of the three stars and not found unambiguously in the Lomb-Scargle periodogram for individual Kepler quarters. The last group consists of KIC 11073910, KIC 11390058, and KIC 11972298, where the light curve shows no distinct pattern, or a periodic behaviour is found only in some quarters. For these stars it is not clear to us what causes the complicated light curve (see also Sect. 4).

Similar beat patterns have been observed, as seen on for instance CoRoT-2 by Huber et al. (2010), who present two different interpretations for the beat pattern. First it can be explained by differential rotation of at least three spots or active regions. Alternatively, it can be explained by a flip-flop effect: there are two active regions on different hemispheres of the star, with one dominating the light curve. During the minimum of the beat pattern, the other active region rapidly becomes the dominant one. This kind of behaviour has also been observed in the pre-*Kepler* era in single stars, using temperature mapping techniques (see e.g. Korhonen et al. 2001).

Most of the stars in our sample show periods that are at least double-peaked, with one peak moving slowly with respect to the other. This slow movement of the two peaks relative to each other identifies the feature as being caused by different spots on the surface of the star. Nevertheless, a double star system cannot be excluded as the origin of this light curve pattern, if both stars are active and are not synchronised. Therefore, all stars in our sample seem to be active, in the sense that they have different spot groups on their surface, manifesting in complicated but periodic light curves. The relative movement of the peaks may be caused by differential rotation of the star, but it may also be caused by spot evolution (see Huber et al. 2010).

4. Individual stars

4.1. KIC 3626094

KIC 3626094 (2MASS J18591491+3845462, TYC 3119-1230-1) has the shortest rotation period within our sample (0.724 d).

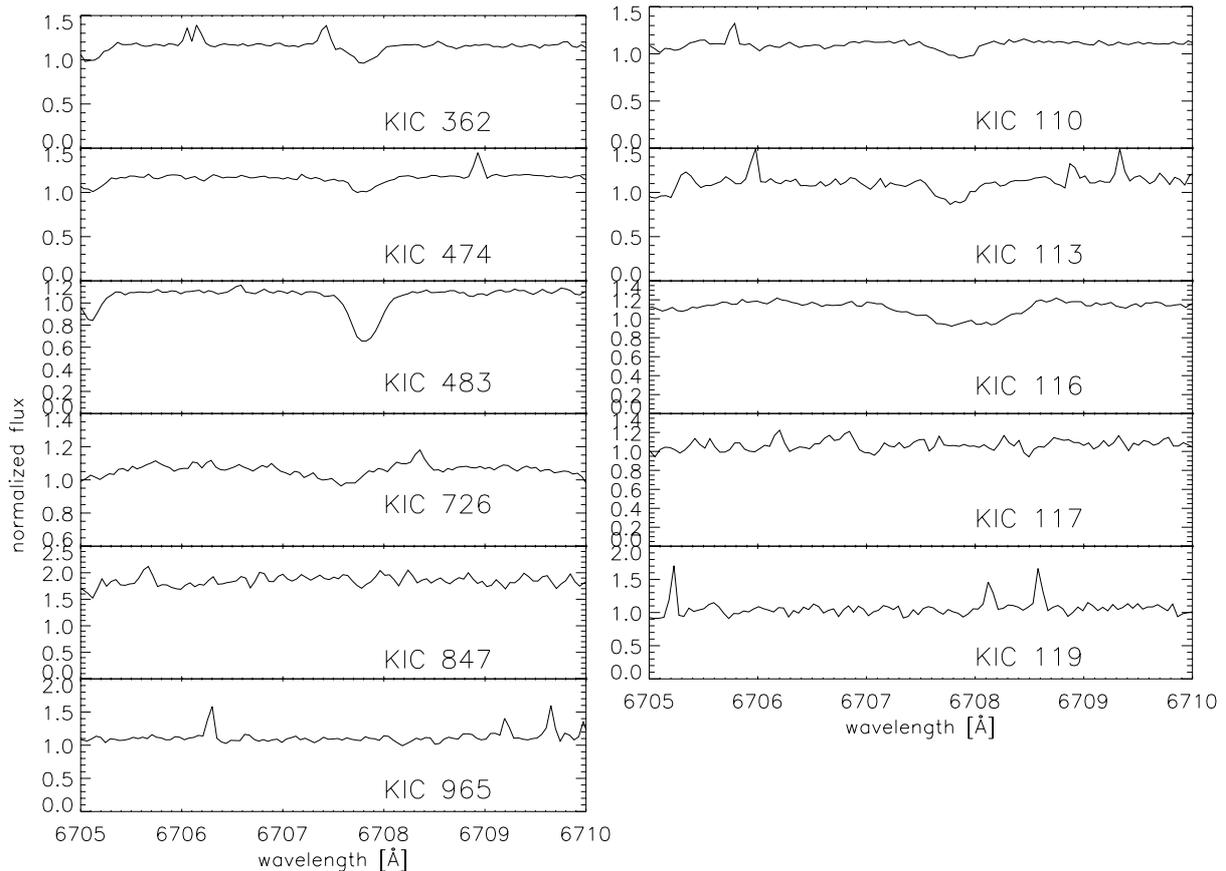


Fig. 3. Spectra of our programme stars showing the wavelength region around the Li I line at 6707 Å.

The spectrum shows no obvious signs of activity, whether compared to the PHOENIX best fit spectrum or to the inactive G0 star. From the chromospheric point of view, KIC 3626094 is the most inactive star of the sample, which agrees well with it not being detected as a ROSAT source. Nevertheless, Li λ 6707 is clearly detected, albeit with an EW below the Pleiades upper limit.

Ultra fast rotators with periods well below one day among G-type stars are typical of young open clusters up to the age of the Pleiades (c.f. Barnes & Sofia 1996). We therefore conclude that KIC 3626094, with its T_{eff} of $\approx 5800\text{--}6000$ K, is a young G0 – G2 star with an age similar to, or less than, the Pleiades (i.e. $\lesssim 125$ Myr).

4.2. KIC 4742436

KIC 4742436 (TYC 3138-950-1) can be identified with the ROSAT X-ray source 1RXS J192149.3+395017 (offset 10.4''), which has a count rate of 0.0121 ct/s and a positional error of 14'' (Voges et al. 2000). Its rotation period of 2.3 days is well below what is observed for G-type stars in the Hyades cluster (see Fig. 1 in Barnes & Sofia 1996), and the Li I λ 6707 line is clearly detected. But with regard to the chromospheric emission lines, this star is one of the most inactive of the sample. KIC 4742436 therefore appears to be a modestly active young G-type star (younger than the Hyades cluster at ≈ 600 Myr).

4.3. KIC 4831454

KIC 4831454 (TYC 3138-1050-1) may be the ROSAT X-ray source 1RXS J192200.0+395957 (offset 22.5''), which is listed

with a positional error of 17'' and a count rate of 0.0166 ct/s. Another sign of its activity is the observed filling-in of Ca II lines, although the H α line is not as strongly filled as for other stars in the sample.

With a period of 5.19 days, the star rotates faster than Hyades stars of comparable B-V (0.74 as measured by TYCHO, Hog et al. 2000). It also shows a relatively strong Li I λ 6707 line, and we conclude that, like KIC 4742436, this star is probably younger than the Hyades.

4.4. KIC 7264976

The spectrum of this star (TYC 3128-361-1) shows a double line profile, indicating that it is a binary star. However, we can detect no measurable velocity variation during our observation run. Also the spectrum obtained during our 2013 run shows no measurable line shifts.

Since it seems very unlikely to have two unrelated stars of similar magnitude at the same position in the sky (within $\approx 1''$), we consider it more likely that the star is a binary with a long period of ~ 270 days and that we observed in both runs near quadrature when the variation in the radial velocities would be slowest. If this assumption is correct, then the star is a relatively wide binary (≈ 1 AU). The binarity would not explain the observed flaring activity as active binaries of the RS CVn type are tight binaries where the stars spin fast because of tidal synchronisation.

The Li I λ 6707 line is clearly detected, although the period of 12.7 days seems to hint at an age in excess of the Hyades cluster. However, since the star is a binary, it is not clear which of the two stars is responsible for the photometric period, and although the error is large, the $v \sin i$ of KIC 7264976A seems to be at odds with the period.

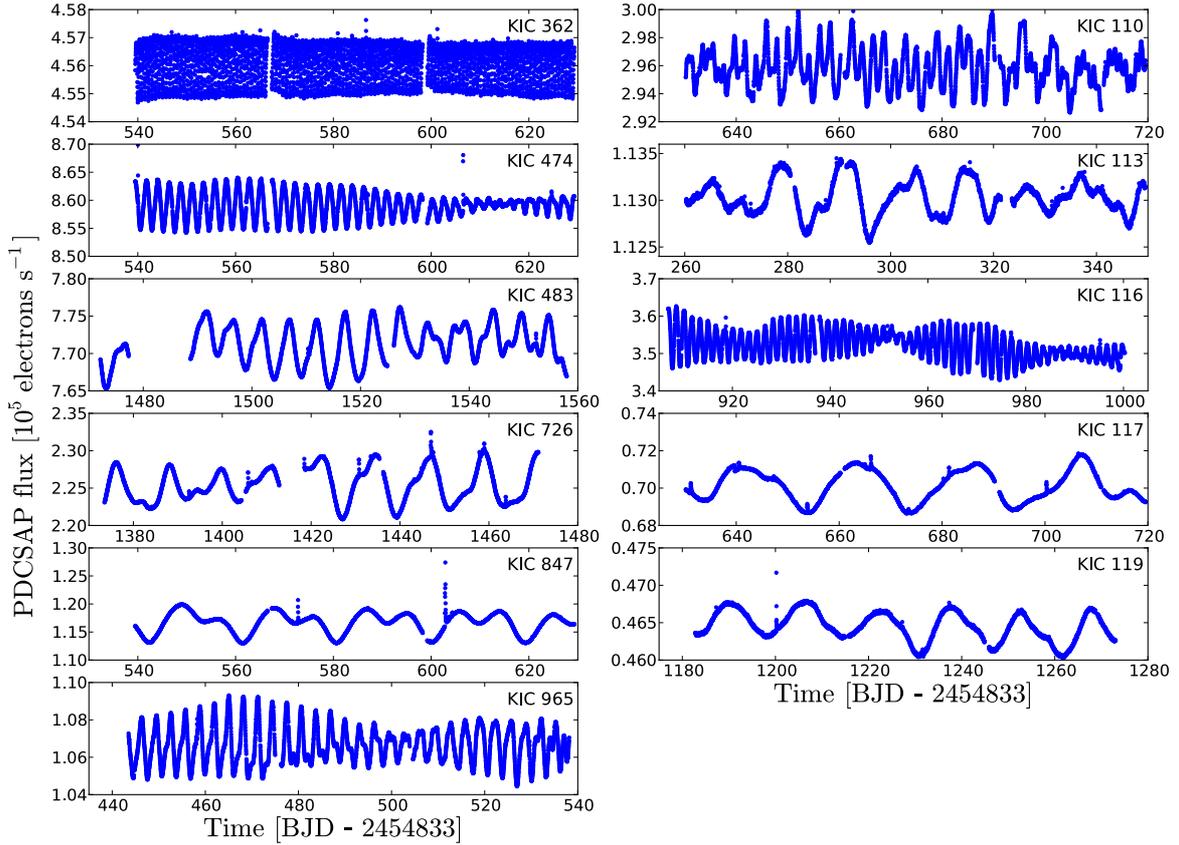


Fig. 4. *Kepler* light curves for the target stars.

Chromospheric activity is seen in some filling in the $H\alpha$ line and in the Ca II infrared triplet.

4.5. KIC 8479655

KIC 8479655 (2MASS J18574324+4435558) does not show the Li I λ 6707 line in its spectrum, although the filling-in of the $H\alpha$ and Ca II lines indicate some chromospheric activity. The $H\alpha$ line shows some asymmetry in the red wing, with an emission component (see Fig. 2). However, this may be caused by noise, since it is the star with one of the lowest S/N in the sample. Therefore, the measured $H\alpha$ EW is presumably too small.

Based on the non-detection of Li I λ 6707 and the photometric period, this star seems to be significantly older than the other ones in our sample, and it is not clear why it shows chromospheric activity and strong flares. It has a long photometric period of 19.3 days, which seems to be inconsistent with the measured $v \sin i$ of $9 \pm 3 \text{ km s}^{-1}$ even if the temperature were significantly in error, since for an F-G main sequence star, we would expect a radius in the range of 0.85 to $1.3 R_{\odot}$ (Zombeck 1990), hence a rotational velocity of $\approx 3\text{--}2 \text{ km s}^{-1}$. The minimum radius of KIC 8479655 is $3.4 \pm 1.2 R_{\odot}$. Our spectroscopically determined $\log g$ value is inconsistent with this star being a giant, although it is compatible with a subgiant. We do not find significant radial velocity variations during the timespan of our 2012 observations, but we cannot rule out that the star may be a wide binary, with a brighter component dominating the spectrum and a fainter component dominating the light curve variations.

4.6. KIC 9653110

KIC 9653110 is a fast-rotating star, but it was not detected in the ROSAT All-Sky Survey. The spectrum has a low S/N that, in

combination with the rotational broadening, makes it impossible to determine whether the Li I λ 6707 line is present or not.

With respect to rotation and temperature, the star appears to be similar to KIC 4831454 and KIC 4742436, and we conclude that like these two stars, it is probably a young star, at least younger than the Hyades. Its chromospheric activity manifests in all investigated lines, they are all filled up. It is the most active star of the sample.

We note that a stellar radius of at least of 5.0 ± 0.6 solar radii is required to reconcile the rotation period with the $v \sin i$ value. While the $\log g$ may be compatible with a subgiant, we find it very unlikely that a subgiant would have a $v \sin i$ of approximately 80 km s^{-1} . Therefore we presume that the star is either a pre-main sequence star, or the rotation period is due to spots on a companion star that is too faint to show up in the spectrum.

4.7. KIC 11073910

KIC 11073910 (TYC 3545-1049-1) is a fast rotator with a clearly detected Li I λ 6707 line, it shows chromospheric activity in all investigated lines, and is the second most active star in the sample. There is a ROSAT X-ray source (1RXS J190429.1+483725) at an offset of $33.2''$, listed with a positional error of $23''$ and a count rate of 0.0267 ct/s .

We conclude that this is a young star with an age lower or equal to the Hyades cluster (based on the observed period). Notably, the T_{eff} listed in the *Kepler* input catalogue is significantly lower than the one we determine from our spectra.

Also, the *Kepler* light curve of this object is different from the other light curves. Though a period can be found using the periodogram (and can also be established by inspecting the light

curve by eye), the light curve shows a lot of additional flickering, the cause of which is not clear. Possible explanations are a multitude of active regions, minor flares, or pulsations. If our inferred stellar parameters are correct, the star is an early-to-mid F star and therefore close to the borderline between stars with and without convection zones. This leaves some doubt as to whether the detected period is really caused by stellar spots. On the other hand, the star has filled in chromospheric lines and seems to be chromospherically active.

4.8. KIC 11390058

All chromospheric lines are filled in to some degree and the star is among the more active ones in the sample. Nevertheless, no ROSAT source was found within a search radius of $120''$. The *Kepler* light curve shows no conclusive behaviour. Some quarters show a periodic pattern of about 12 days as shown in Fig. 4. But this period is not found for every quarter. Some of these other quarters exhibit different periods, but some also look very irregular without a clear periodic behaviour. We attribute this behaviour to changing spot patterns.

Although the light curve hints at a slow rotation period, the spectrum clearly shows the Li I $\lambda 6707$ line, with an EW somewhat less than the Pleiades upper limit, indicating that this is a young star.

4.9. KIC 11610797

KIC 11610797 (TYC 3551-1852-1) shows a Li I $\lambda 6707$ line with an EW clearly in excess of the Pleiades upper limit, indicating that it is significantly younger than the Pleiades cluster (125 Myr). It is also a rapid rotator and shows clear indications of chromospheric activity in most of the lines we investigated. We do not detect any filling-in of the H γ and H δ lines, which may be caused by the rotational broadening of the lines, the low S/N, and problems in determining a continuum in this wavelength region. Also this star shows an asymmetry in the red wing of the H α line, with additional absorption. This asymmetry seems to be real and not caused by noise. Unfortunately, the additional absorption component is very broad, extending from about 6563 to 6564.5 Å and not deep enough to be fitted with an additional Gaussian or Voigt profile.

This is most probably a very young star, and as with several other stars of our sample, there is an X-ray source (1RXS J192737.8+493949) detected nearby (offset $27.5''$, listed with a positional error of $27''$ and a count rate of 0.0186 ct/s).

4.10. KIC 11764567

There is no ROSAT source within $120''$ of KIC 11764567. The rotational period of 20.5 d and the non-detection of Li I $\lambda 6707$ indicate that this is probably an old star. However, just as in the case of KIC 8479655, the $v \sin i$ is much too large for a main sequence star of this rotation period. The minimum radius is $8 \pm 1.2 R_{\odot}$. We have four spectra of this star (three from Aug. 22, 2012, one from Aug. 17, 2012), but the S/N of the individual spectra is too low to check for line shifts. Given the discrepant values of $\log g$ determined by both methods used and not detecting the Li line, the star may either be evolved or be a binary. However, the $v \sin i$ seems too high for an evolved star.

All measured chromospheric lines show some filling-in. Therefore, we consider the star to be active.

4.11. KIC 11972298

The spectrum of KIC 11972298 is noisy and nearly all chromospheric lines are hampered by cosmics. Nevertheless, all investigated chromospheric lines are filled in, and the star is amongst the most active stars of the sample, from the chromospheric point of view. There is no ROSAT source within $120''$ of KIC 11972298. The noise level meant we could not perform EW measurements of the Li I $\lambda 6707$ line.

The *Kepler* light curve exhibits regular periodic behaviour in some quarters, but in other quarters the light curve seems to show chaotic behaviour, though the periodogram finds significant periods for every quarter. Many quarters show a period of about eight days, some a period of 14 to 16 days. Also other significant periods are found in individual quarters. It is somewhat unclear, whether the eight-day period is an alias of the 14- to 16-day period. The period for quarter 13 shown in Fig. 4 is 15.6 days. It remains unclear what causes this irregular behaviour. A possible explanation is quickly evolving spots, but there are other possibilities, such as pulsations.

As with some other stars in our sample, the $v \sin i$ is much too large for a main sequence star of this rotation period. The minimum radius is $5.6 \pm 3.5 R_{\odot}$. Again, the star might either have a faint companion that is responsible for the photometric variability or it is not a main sequence star. In the latter case, since we cannot rule out the presence of a Li line it may either be an evolved star or a pre-main sequence star.

5. Discussion

Flares on low-mass main sequence stars are caused by solar-type magnetic activity, and it is well known that this activity depends chiefly on rotation. Hence, the most active stars are those that are fast rotators, either because they are young or because they are in close binary systems.

Young stars have spun up during contraction towards the main sequence, but have not yet had time to spin down by magnetic braking, i.e. the interaction of their magnetic fields with the wind. Close binary stars can be fast rotators irrespective of their age owing to synchronisation of their rotational and orbital periods caused by tidal forces. On the other hand, even slowly rotating solar-type stars can occasionally show relatively strong activity, as shown, for instance, by the famous white-light Carrington flare on the Sun (Carrington 1859).

Kepler has provided an unprecedented data set of photometric observations. Never before has such a large sample of stars been observed at high cadence for a long period of time, and that makes it difficult to place the results in context. For example, the observed super flares might be typical of active young stars, but there is no young open cluster in the *Kepler* field to confirm this.

Maehara et al. (2012) divide their sample into fast (period ≤ 10 d) and slow rotators (period > 10 d), with the former presumably young, while the latter are termed “Sun-like” by them. Our spectroscopic observations confirm that the fast-rotating stars indeed show Li I $\lambda 6707$ absorption lines, indicative of their youth. Several of them can also be identified with X-ray sources from the ROSAT All-Sky Survey.

Of the five slowly rotating stars in our sample, two (KIC 7264976 and KIC 11390058) also show Li I $\lambda 6707$ absorption and might be young objects. We note that for KIC 7264976, it is not known which of the two components of this binary star causes the photometric period.

The three other slow rotators (KIC 8479655, KIC 11764567, and KIC 11972298), as well as one fast rotator (KIC 9653110) show a puzzling discrepancy between the observed photometric rotation period and the measured $v \sin i$ that requires a minimum radius exceeding the expected value (for a main sequence star) by a factor of 2–8 for each of these stars. We hypothesise that these stars are either evolved (or pre-main sequence, when the Li line cannot be measured), or they are binaries where the photometric period originates in the less massive component, while the spectrum is dominated by the more massive one. We note that within errors, the measured values of $\log g$ might be compatible with these stars being subgiants, which would relax the tension between rotation period and $v \sin i$. However, because of the magnetic braking experienced during their main sequence life, stars in this mass range would be slow rotators at the end of their main sequence life and become even slower when evolving towards the giant branch. We do not consider it likely that stars with $v \sin i$ significantly in excess of the Sun are evolved subgiants.

In conclusion we find no general picture of the analysed super-flare stars. Though many of them show indicators of youth that would be a straightforward explanation of the exhibited super-flares, for others the situation is not so clear or even puzzling. Besides the individual discrepancies discussed above, two of the stars showed very little chromospheric activity during our observations, several stars – in particular more than half of the slow rotators – apparently have minimum radii in excess of main sequence stars, and some stars cannot be associated with ROSAT sources. Therefore, more observations of super-flare stars are needed in order to discover some common element or to confirm that super flares are possible on a wider variety of stars.

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