WHITE-LIGHT FLARES ON CLOSE BINARIES OBSERVED WITH KEPLER

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ABSTRACT

Based on Kepler data, we present the results of a search for white light flares on 1049 close binaries. We identify 234 flare binaries, of which 6818 flares are detected. We compare the flare-binary fraction in different binary morphologies (“detachedness”). The result shows that the fractions in over-contact and ellipsoidal binaries are approximately 10%–20% lower than those in detached and semi-detached systems. We calculate the binary flare activity level (AL) of all the flare binaries, and discuss its variations along the orbital period (P_{orb}) and rotation period (P_{rot}, calculated for only detached binaries). We find that the AL increases with decreasing P_{orb} or P_{rot} up to the critical values at P_{orb} ~ 3 days or P_{rot} ~ 1.5 days, and thereafter the AL starts decreasing no matter how fast the stars rotate. We examine the flaring rate as a function of orbital phase in two eclipsing binaries on which a large number of flares are detected. It appears that there is no correlation between flaring rate and orbital phase in these two binaries. In contrast, when we examine the function with 203 flares on 20 non-eclipse ellipsoidal binaries, bimodal distribution of amplitude-weighted flare numbers shows up at orbital phases 0.25 and 0.75. Such variation could be larger than what is expected from the cross section modification.

Key words: binaries: close – stars: activity – stars: flare

Supporting material: figure set, machine-readable tables

1. INTRODUCTION

Flares are short-lived and intense releases of magnetic energy that are caused by the reconnection of magnetic field loops in the outer atmospheres of stars (e.g., Benz & Güdel 2010; Shibayama et al. 2013). The typical energy release in a solar flare ranges from 10^{27} to 10^{32} erg, and the duration is usually a few minutes to several hours. Ground-based observations show that stellar flares are typically few minutes or hours and are typically 10–1000 times more energetic than solar flares (e.g., Güdel & Nazé 2009). Nine G-type dwarf superflare candidates with typical energies of 10^{34}–10^{35} erg have been reported by Schaefer et al. (2000). Such a search was extremely extended by Shibayama et al. (2013), in which 1547 superflares were found on 279 G-type dwarfs from Kepler.

The Kepler spacecraft is quite powerful at detecting stellar flares due to its high-precision (~0.1 mmag) and long-period time-series observations (Koch et al. 2010). Since its launch, the number of flare stars in a variety of stellar types has been dramatically increased; for instance, 373 flaring stars among ~23,000 cool dwarfs are in the Kepler Quarter 1 LC data (Walkowicz et al. 2011), flare A-type stars have been detected in the Kepler field (Balona 2013), and 148 G-type superflare stars are found from ~83,000 stars observed over 120 days (Maehara et al. 2012). Meanwhile, our knowledge of the typical energies of stellar flares has increased further. Most of the flares caught with Kepler are 10^{–2}–10^{3} more intense than the large solar flares, which should be identified as “superflares” if coming from the ground-based observations.

Flares were also discovered on binaries, e.g., RS CVn variables (Pandey & Singh 2012) and a W UMa star (CSTAR 038663; Qian et al. 2014). RS CVn is a class of detached binaries typically composed of a chromospherically active G or K star (e.g., Berdyugina & Järvinen 2005). The underlying mechanisms of triggering flares on RS CVn are expected to remain the same because in the single stars the magnetic reconnection in the field connecting the two stars may cause the flare events to be more active (e.g., Gunn et al. 1997), and tidal effects play important roles for enhancing the magnetic activity of RS CVn stars (Cuntz et al. 2000). Flares on CSTAR 038663 are expected to originate on the surface of the contact binaries based on the observational facts that, (i) the flare amplitude is increasing along the duration, and (ii) the photometric solution reveals a long-lived dark spot on the contact binary, which could be associated with the flares (Qian et al. 2014). Using Kepler data, Balona (2015) examined the flare frequency as a function of orbital phase in three eclipsing binaries. Unfortunately, no correlation between flaring and orbital phase was established from the work, and the result weakens the hypothesis that flares in close binaries could be a result of the reconnection of the field lines connecting the two stars (Balona 2015).

The main goal of this work is to identify flare binaries from Kepler data, and to investigate the correlations between flare properties and the physical parameters of binary systems. In order to achieve this purpose, we analyzed the light curves of 1049 close binaries, identified 234 flare binaries, and discovered 6818 flares on them. In Section 2, we describe the criteria for working-sample selection and the method of flare identification. In Section 3, we discuss the flaring properties of two “peculiar” systems in Section 3.1, i.e., the Kepler-Input-Catalog (KIC) 5952403 (a triple star system) and KIC 11347875 (a binary with an asymmetric light curve), we detect the flaring rate along the flare intensity and binary morphology in Section 3.2, along the orbital period and rotation in Section 3.3, and along the orbital phase in Section 3.4. The conclusion and discussion are provided in Section 4.
2. OBSERVATION AND DATA ANALYSIS

2.1. Kepler Data

The *Kepler* spacecraft was launched by NASA in 2009 March with the primary objective of searching for exoplanets by finding planetary transit events from the recorded light curves of target stars in the Cygnus, Lyra, and Draco regions (Borucki et al. 2011). Because the luminosity decrease from planetary transit is usually less than one-hundredth of the total brightness of the star and the planet can be observed in front of the star only when the orbit is nearly parallel with the line of sight, *Kepler* is thus designed to obtain high-precision and long-term light curves of over 190,000 stars. The typical photometry precision is 0.1 mmag for a star of 12 mag, and the photometry was continuously processed and recorded for a period of four years (Gilliland et al. 2010b; Koch et al. 2010). Therefore, the *Kepler* light curves are useful for detecting not only planetary transits but also other small brightness variations such as stellar flares.

*Kepler* has two kinds of data records, which are specified with their time resolutions, i.e., long cadence (LC) of 29.4 minutes exposure and short cadence (SC) of 1 minute of exposure. Flare detection from *Kepler* is confined to the LC exposure time. The 30 minute exposure prohibits the detection of short-lived flares and greatly lowers the visibility of flares lasting less than one or two hours. SC exposure is more suitable for the study of stellar flares (Maehara et al. 2015). Unfortunately, SC data are available for only 4828 stars and the time coverage is usually less than two months (Gilliland et al. 2010a).

2.2. Sample Selection

*Kepler* light curves are released in two types, i.e., the original simple aperture photometry, and with the pre-search data conditioning (PDC). The instrumental effects and some other errors such as flux discontinuities are removed from the PDC data (Smith et al. 2012). Because the first step of the work is to identify as many flare binaries as possible, a sufficient working sample in accurate photometry can certainly help making the statistical results more reliable, therefore in this work we choose the *Kepler* LC-PDC data.

The *Kepler* eclipsing binary (KEB) catalog (released on 2015 June 6 (Kirk et al. 2015)) includes more than 2800 binary stars identified from *Kepler* data. KEB provides the binary information of its KIC identifier, morphology type, binary period, coordinates, *Kepler* magnitude, etc., among which the morphology is valued from 0 to 1, matching with the binary type from detached (0–0.5), to semi-detached (0.5–0.7), to over-contact (0.7–0.8), to the ellipsoidal (0.8–1.0) binaries, using the method of locally linear embedding (Matijević et al. 2012).

We select 1049 out of the over 2800 binaries in KEB as our working sample, based on three main criteria: (1) binaries with neighboring stars within 12 arcsec are excluded to avoid false events from the flux of the neighboring stars (Shibayama et al. 2013); (2) the orbital period is longer than 0.4 days, since the light curves with periods of less than 0.4 days are easily entangled with the flare profiles; and (3) because we use the 30 minute exposure LC data, given the period of 0.4 days, there has to be more than 20 data records within one orbital period; otherwise, the decomposition of flares from the binary light variation may become impossible. Meanwhile, some “peculiar” targets are also excluded from the working sample, which are mainly: (1) 42 heartbeat binaries with highly eccentric orbits and tidally induced pulsations, excluded because their light curves are unable to be understood with a 4-terms Fourier function that we adopt in the work for flare detection (detailed description of the method is given in Section 2.3); (2) 88 targets that are not binaries, i.e., single stars with stable dark spots and multiple-star systems; and (3) 17 KIC targets without valid morphology values.

2.3. Flare Measurements

The flare detection efficiency is limited by the data mode and the photometric uncertainty. Besides the disadvantage of using the long-time-exposure LC data, there is another difficulty that we need to confront, i.e., due to the fact that the flare detection is based on the measurement of the light curve variations, a detrend process is definitely required to eliminate the baseline flux off the light curve.

Given that the ellipsoidal binaries have the smoothest binary light curves with quasi-sinusoidal variations, and that the variations can be understood with no more than a 3-terms Fourier series (Morris 1985), we decide to use a 4-terms Fourier series to trace all the binary light curves without any smoothness except for the detached systems, as we are working on a large binary sample that includes different morphology types.

As for the detached binaries, the two components have no interaction or mass exchange between each other, and thus they can be considered as two “isolated” single stars; therefore, the baseline fitting for detached binaries follows the method adopted in the work of flare detection on cool single stars by Walkowicz et al. (2011), i.e., a median filter observes the light curves on which the flares have been tagged out and then creates the baseline curve with quiescent variability but no flares. The data points during eclipse are excluded.

The main procedure of baseline fitting for the other three morphology types follows these steps.

i. The observed light curve is fitted with a 4-terms Fourier series in each orbital period. The data that are 3σ away from the Fourier fitting curve will be eliminated. The process iterates until all the data left are within 3σ.

ii. The remaining data after step (i) are fitted again with 4-terms Fourier series. This time, the fitting is repeated 10 times with a 0.1 orbital period backward each time, which means each observing data point refers to 10 fitting points.

iii. The average and standard deviations of the 10 fitting points are calculated for each data point. Any fitting points 1σ away from the average are discarded.

6 The stable dark spots rotate together with the single star, which makes the light curve of the single star very easy to misclassify as the light curve of the ellipsoidal binary. It can be distinguished as such as the flip-flop phenomenon (Jetsu et al. 1994; Jetsu 1996) and the amplitude diminishing on the light curve due to the weakening or vanish of the dark spots.
iv. Finally, the baseline curve is established by taking the $\sigma$-clipped robust mean value of the fitting points left after step (iii).

v. When the method is applied to the semi-detached and over-contact binaries, the data points during eclipsing are simply excluded.

Figure 1 demonstrates the procedure of baseline fitting. The light curve of KIC 11457191, a semi-detached binary, is used as an example. The original light curve is plotted in gray lines. The remaining data for the baseline as an example. The original light curve is plotted in gray lines. The black dots are the remaining data points after the $3\sigma$ exclusion in step (i) (Section 2.3). As KIC 11457191 is a semi-detached binary, data points during eclipsing are also excluded. Panel (b): 10 times the fitting points in step (ii) are given in green lines. The outliers clearly show up around the discontinuities (green line). Panel (c): the baseline curve (red line) is established by connecting the $\sigma$-clipped robust mean value of the fitting points (the green line in panel (b)).

There are various flare detection algorithms (e.g., Walkowicz et al. 2011; Osten 2012). As a general description, light curves are analyzed after they have detrended, i.e., the baseline curve has been subtracted from the observed light curve, and are searched for brightness enhancement where the relative flux becomes statistically larger than a certain threshold for two or more times consecutively. In this work, we combine the algorithms of Walkowicz et al. (2011) and Shibayama et al. (2013) to identify flare binaries.

i. Events are flagged as flare candidates when a minimum of 3 contiguous points are found above a threshold of 3 times the standard deviation of the local quiet flux.

ii. We calculate the number distribution of brightness variation between all pairs of two consecutive data points for all the binary stars.

iii. Brightness variation from step (ii) is identified as flare when the event is marked as a flare candidate from step (i) and it matches the threshold of the “1%” number distribution from step (ii) (as presented in Figure 1(b) in Shibayama et al. 2013).

iv. Pairs of flares that occurred at the same time and whose spatial distances are less than 24 arcsec are excluded. About 12% of flares are rejected in this process.

v. As a final step, the pixel level data of each remaining flare from step (v) are examined by eye. If the spatial distribution of a flare on the CCDs is different from the distribution of the most energetic quiescence, the flare is considered as a brightness variation of another source (Shibayama et al. 2013; Kitze et al. 2014). About 12% of flare candidates are removed in this step.

3. DATA RESULTS AND ANALYSIS

Following the method described in the previous section, we identify 234 flare binaries from the 1049 close binary samples. 6818 flares are detected on flare binaries. The fundamental parameters of the 234 flare targets and the 6818 flares (together with light curves) are available electronically. Tables 1 and 2 give the excerpt from the overall tables.

Figure 2 shows examples of the flare light curves on six close binaries. The horizontal and vertical axes correspond to the time (day) from the flare, and the relative flux $\Delta F/\bar{F}$ from...
Table 1
Fundamental Parameters of 234 Flare Binaries

| KIC  | $T_{\text{eff}}$ (K) | log g | $P_{\text{obs}}$ (day) | Mor | Amp | AL | $f$ (1/day) | $N_i$ | log ($\Delta F_{\text{max}}/F$) | DR$_{\text{min}}$ |
|------|-----------------------|-------|------------------------|-----|-----|----|-------------|------|-----------------------------|-------------|
| 002305372 | 5664                  | 3.974 | 1.405                  | 0.58 | 0.066 | 1.232e-05 | 0.015 | 20 | -1.043                  | 24          |
| 002447893 | 5059                  | 4.447 | 0.662                  | 0.58 | 0.043 | 1.415e-05 | 0.016 | 21 | -1.296                  | 24          |
| 002556127 | 5920                  | 4.629 | 0.419                  | 0.59 | 0.003 | 5.365e-08 | 0.001 | 1  | -2.583                  | 24          |
| 002557430 | 6248                  | 4.103 | 1.298                  | 0.51 | 0.010 | 6.314e-06 | 0.060 | 81 | -2.040                  | 24          |
| 002569494 | 5114                  | 4.471 | 1.523                  | 0.58 | 0.186 | 8.435e-05 | 0.058 | 25 | -1.264                  | 24          |
| 002577756 | 5630                  | 4.953 | 0.870                  | 0.63 | 0.094 | 2.946e-06 | 0.007 | 10 | -1.775                  | 24          |
| 002835289 | 6228                  | 4.265 | 0.858                  | 0.92 | 0.023 | 3.431e-06 | 0.011 | 15 | -1.584                  | 24          |
| 003114667 | ...                   | ...   | ...                    | ... | ...  | ...         | ...   | ... | ...                      | ...         |
| 003218683 | 5119                  | 4.659 | 0.772                  | 0.69 | 0.173 | 2.602e-05 | 0.007 | 10 | -0.856                  | 24          |
| 003338660 | 5722                  | 4.276 | 1.873                  | 0.60 | 0.077 | 1.904e-05 | 0.018 | 14 | -1.031                  | 24          |

Note. The KIC number, effective temperature ($T_{\text{eff}}$), surface gravity (log g), orbital period ($P_{\text{obs}}$), and morphology value (Mor) are extracted from the KEB catalog. The light curve amplitude (Amp), flare activity level (AL), flare frequency ($f$ flares/day), total number of flares ($N_i$), and the peak relative flux of flares (log($\Delta F_{\text{max}}/F$)) are calculated in the work. $\Delta F_{\text{max}}$ is calculated by substituting $F$ of the highest energy flare into Equation (1). DR$_{\text{min}}$ is the LC-PDC data release version that we adopt for each flare binary.

(This table is available in its entirety in machine-readable form.)

Table 2
Parameters of the 6818 Flares

| KIC  | $t_{\text{max}}$ (day) | EW (day) | $\Delta F/F$ | $\Delta t$ (hr) |
|------|------------------------|----------|--------------|-----------------|
| 002305372 | 5143.30545           | 0.000140 | 0.003621     | 1.471141       |
| 002305372 | 5159.56975           | 0.000277 | 0.001817     | 1.961526       |
| 002305372 | 5166.43511           | 0.000086 | 0.001994     | 1.471150       |
| 002305372 | 5297.29229           | 0.000299 | 0.005592     | 1.961720       |
| 002305372 | 5422.18660           | 0.001007 | 0.012124     | 4.904034       |
| 002305372 | 5446.23655           | 0.001099 | 0.043413     | 1.471182       |
| 002305372 | 5458.53721           | 0.000930 | 0.011786     | 4.413509       |
| 002305372 | 5511.41691           | 0.001581 | 0.019670     | 4.413426       |

Note. The columns are: (1) the KIC number, (2) the time of flare maximum ($t_{\text{max}}$) relative to BJD 2450000, (3) EW (days), (4) relative flux amplitude ($\Delta F/F$), and (5) flare duration ($\Delta t$ (hour)). The complete table and the light curve amplitudes are available online.

(This table is available in its entirety in machine-readable form.)

Equation (1), respectively. In each panel in Figure 2, the black, green, and red lines represent the light curves of the observed data, the baseline fitting flux, and the flares, respectively. The KIC number of each binary is given in the upper right corner in each panel.

$$\Delta F/F = (F - \bar{F})/\bar{F},$$  \hspace{1cm} (1)

where $F$ is the observed flux from LC-PDC data, $\bar{F}$ is the average flux during the current observation quarter.

Based on the light curves, there are basically two detectable parameters regarding flare properties. One is the total number of flares ($N_i$) during the entire observing period, and the other is the corresponding flare intensity. $N_i$ is directly obtained from flare detection. The measurement of flare intensity is processed with Equations (2) and (3).

For each flare, we integrate the points that are tagged as part of the flare, which is essentially a photometric equivalent width (EW) of the flare (Walkowicz et al. 2011), i.e.,

$$\text{EW} = \int \frac{F_t - F_q}{F_q} dt,$$  \hspace{1cm} (2)

where $F_t$ and $F_q$ are the flaring and the quiescent flux, respectively. The observed flare energy is interpolated with the cubic spline function for the EW integral. The integral starts and ends at the baseline curve, and the interpolation usually includes 1000 grids. We compare the EW results when performing the integral with or without spline interpolation. Two flares, one with a 1.5 hr duration and 6 data points, the other with a 13 hr duration and 29 data points, are used as the sample. The results show that: (1) for the 6-point flare, the EW difference is 9.6%; and (2) for the 29-point flare, the difference is 1.1%. As we mentioned in the previous section, the SC data are actually more suitable for the studies of stellar flares compared to the LC data (Maehara et al. 2015). Shibayama et al. (2013) showed two examples of the flare energy differences from using SC and LC data; there is no energy difference for the flare in Figure 11, and the SC result is 20% larger than the LC result in Figure 12 (see Appendix A in their paper). Considering that flares in SC data are sampled more sufficiently, and thus should present higher (at least equal) flare energy compared to those in LC data, the cubic spline interpolation we adopt in the EW integral will not artificially expand the flare intensity and will decrease the possibility of underestimating the EW.

Such an EW quantity actually has units of time. It can be intuitively thought of as the time interval over which the quiescent star emits as much energy as that released during the flare. Meanwhile, EW is a differential quantity, independent of distance and measured relative to the quiescent star. Therefore, for one binary system, the summation of the EWs of all the flares divided by the total observation time can provide a measurement of the flaring intensity, which is defined as the flare “activity level” (AL) in the work:

$$\text{AL} = \frac{\sum_{i=1}^{N_i} \text{EW}_i}{T_{\text{obs}}} \approx \frac{E_t}{E_q},$$  \hspace{1cm} (3)

where $\text{EW}_i$ is the EW of the $i$th observed flare on a binary. $T_{\text{obs}}$ is the entire observation time of the binary. Assuming that the binary quiescent radiation is a relatively stable value, i.e., $F_q$ in Equation (2) is approximately a constant, the description of $(F_q \times T_{\text{obs}})$ thus represents the total energy of the quiescent

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8 To our knowledge, the concept of “AL” is here used for the first time to estimate the ratio of flare energy over quiescent radiation energy.
radiation \( (E_q) \), the value of \( (F_i \times \sum_{i=1}^{N_i} EW) \) is the total energy of all the flares \( (E_i) \), and therefore the AL value actually estimates the ratio of \( E_i/E_q \).

Figure 3(a) presents the number distribution of flare binaries \( (N_{fb}) \) along the log AL values. The black line in the figure represents the \( N_{fb} \) distribution of the total 234 flare binaries. The red, green, blue, and magenta lines are the \( N_{fb} \) distributions of the detached, semi-detached, over-contact, and ellipsoidal flare binaries, respectively. The black line shows two peaks at log AL around \(-4.5\) and \(-5.5\). The “\(-4.5\)” peak is mainly contributed by the detached (red line) and semi-detached (green line) systems, which indicates that more energetic flares occur on these two types compared to the over-contact and ellipsoidal systems. Figure 3(b) presents the distribution of \( N_{fb}/N_b \) along log AL. Because AL can only be calculated for flare binaries, the \( N_b \) value is distinguished only for binary types when calculating \( N_{fb}/N_b \) in different log AL bins.

The actual number of binary systems \( (N_b) \) in our working sample and the ratio of \( N_{fb}/N_b \) in different morphologies are listed in Table 3, which shows that the detached and semi-detached binaries occupy 78% of the entire working sample (column 2), 86% of the flare binaries are from these two types (column 3), and the \( N_{fb}/N_b \) ratios in these two types are 10%–20% higher than those in over-contact and ellipsoidal binaries (column 4). A detailed discussion is presented in the following section.

### 3.1. KIC 5952403 and KIC 11347875

As all the flare candidates are finally confirmed by eye, the process provides us with a unique opportunity to confront “peculiar” flare binaries. We pay special attention to two of...
### Table 3

| Morphology          | \(N_b\) | \(N_{fb}\) | \(N_{fb}/N_b(\%)\) |
|---------------------|---------|-----------|-------------------|
| Detached            | 632     | 140       | 22.15             |
| Semi-detached       | 188     | 62        | 32.98             |
| Over-contact        | 59      | 7         | 11.86             |
| Ellipsoidal         | 170     | 25        | 14.71             |
| All                 | 1049    | 234\(^\text{a}\) | 22.31             |

**Note.** The columns are: (1) morphology type of the binary system, (2) number of binaries, (3) number of flare binaries, (4) the ratio of flare binaries in the same morphology.

\(^\text{a}\) We identify 234 total flare binaries from the 1049 binary samples. The two peculiar systems (KIC 5952403 and KIC 11347875) discussed in Section 3.1 are excluded from Figure 3 and Table 3 to avoid the infusion of atypical flare features.

One flare is actually observed on KIC 5952403 during the secondary eclipse from the Kepler SC data (Czesla et al. 2014). It does not appear at phase 0.5 in our Figure 5(a), as we use LC data in this work. The flare occurs when the dwarf pair is hidden behind the giant; it is thus definitely ascribed to the red giant. Seven flares in total are reported by Czesla et al. (2014) in the Kepler SC light curve of KIC 5952403. The authors argued that all these flares should have originated on the red giant because the peak flare luminosity that they calculated is comparable to or even higher than the total luminosity of the dwarf pair, or it would require an unreasonably large region on the dwarfs to reproduce such a flare peak.

Following the same discussion as in Section 5.4.1 in Czesla et al. (2014), Table 4 gives the properties of the 19 flares identified in the Kepler LC data in this work. According to the column 2 information in Table 4, the peak luminosities of the 19 flares range between 0.22% and 1.72% of the giant’s luminosity (\(L_{bol, giant} \sim 92.8 \pm 7.6L_\odot\), Table 1 in Czesla et al. 2014), which refers to 0.2–1.6 \(L_\odot\). Assuming that the flaring material seen by Kepler has a temperature of \(T_{eff} \sim 10,000\) K, and the dwarf stars have radii of \(R_s \approx 0.8 R_\odot\) (Czesla et al. 2014 and references therein), and using the formula of \(f = \frac{2L_{peak}}{\sigma T_{eff}^4 R_s^2}\), we estimate that between 6% and 53% of the visible hemisphere of either dwarf star has to be covered by flaring material in order to produce such flare peaks, which are too much larger than current observation evidence, e.g., an unusually intense flare observed on EV Lac star requires \(\approx 3\)% hemisphere coverage (Osten et al. 2010). In contrast, it requires only 0.03%–0.19% coverage if the flares occur on the giant. It seems that the observation from this work supports the conclusion in Czesla et al. (2014) that the giant is more likely to be the birthplace of all the flares.

KIC 11347875 is a binary system. Its orbital period is \(P = 3.4551\) days (from KEB catalog). Both KIC parameters (\(T_{eff} = 4656\) K, \(\log g = 2.581\)) and the study of Armstrong et al. (2014) indicate that the system contains two late type red giants. The \(T_{eff}\) and \(\log g\) parameters are extracted from the KIC.\(^\text{10}\) Figure 6 gives the light curve and the flare number distributions of KIC 11347875. There are 49 flares detected on the system. These flares (red dots in the bottom panel in Figure 6) are more frequently captured around phase 0.7–0.8. In the bottom panel in Figure 6, both observed light curve (black dots) and their mean values (yellow lines) are in asymmetric shape against phase 0.5, and the shape stays almost invariable during the entire observing time (over 1500 days). If the asymmetric shape and the flare generation are related to the active stellar spot region, then this implies that the movement of the group of spots is synchronized with the orbital motion, and the group of spots may cause the non-axisymmetry distribution of the magnetic fields in the system (Berdynigina & Tuominen 1998).

#### 3.2. Effect of Morphology

Figure 7 shows the \(A_{Lave}\)\(^\text{11}\) variation along the morphology values for all 1049 binaries. As presented in the figure, flare activities are more frequently generated on the detached \((\text{Mor} < 0.5)\) and semi-detached binaries \((0.5 < \text{Mor} < 0.7)\) compared to the contact systems. We also notice that the \(A_{Lave}\)
Variation is related to the interacting activities between two components in a binary, more specifically, $\Delta L_{ave}$ increases monotonically with increasing morphology values for detached binaries, $\Delta L_{ave}$ decreases with increasing morphology values for semi-detached and over-contact binaries, and $\Delta L_{ave}$ keeps roughly constant for ellipsoidal binaries. $\text{Mor} > 0.5$ means that at least one of the components has filled its Roche lobe and mass transfer has begun. The two components become closer as

Figure 4. Light curves of 19 flare events detected on KIC 5952403. The flares are highlighted by red lines. The x-axis is the time (days) from the flare. The y-axis is the relative flux ($\Delta F/F$) of the light curve. MJD is given on the top of each panel.

Figure 5. Flare number distribution of KIC 5952403 when the light curves are folded with $P_{\text{A-BC}} = 45.5178$ days (panel (a)) and with $P_{\text{BC}} = 0.9057$ days (panel (b)), respectively. Bottom panels: the black dots and the yellow lines present the orbital phase folded light curves of the primary and the robust mean values of the light curves, respectively; the red dots are the observed flares. Top panels: amplitude-weighted flare number distributions ($N_f^*$) along the orbital phase. Middle panels: normal flare number distributions ($N_f$) along the orbital phase.
those fast rotating detached binaries of over-contact binaries variation starts becoming invisible in this condition. The $\Delta L_{\text{ave}}$ Mor becomes larger. When Mor

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\begin{align*}
\text{Table 4} & \quad \text{Properties of the 19 Flares in the Kepler Long-cadence Light Curve of KIC 5952403} \\
T_{\text{peak}}^a & \quad f_{\text{peak}}^b & \quad t_{\text{rise}}^c & \quad t_{\text{decay}}^c & \quad E_{\text{flare}}^d \\
(\text{day}) & \quad (%) & \quad (\text{minute}) & \quad (\text{minute}) & \quad (\text{erg}) \\
159.916 & 0.47 & 59 & 221 & 2e + 38 \\
194.736 & 0.60 & 29 & 265 & 3e + 38 \\
269.685 & 0.81 & 59 & 103 & 3e + 38 \\
278.553 & 0.81 & 118 & 206 & 4e + 38 \\
297.984 & 0.38 & 103 & 250 & 2e + 38 \\
362.610 & 1.72 & 15 & 206 & 4e + 38 \\
405.217 & 0.45 & 118 & 309 & 3e + 38 \\
424.589 & 0.26 & 29 & 250 & 4e + 38 \\
447.312 & 0.25 & 88 & 177 & 1e + 38 \\
471.322 & 0.87 & 74 & 324 & 3e + 38 \\
497.969 & 0.22 & 74 & 368 & 2e + 38 \\
500.748 & 0.26 & 250 & 177 & 1e + 38 \\
549.095 & 0.50 & 162 & 309 & 3e + 38 \\
572.267 & 0.26 & 250 & 44 & 1e + 38 \\
605.022 & 0.26 & 29 & 250 & 1e + 38 \\
613.747 & 0.27 & 59 & 191 & 8e + 37 \\
613.747 & 0.57 & 103 & 485 & 3e + 38 \\
1321.424 & 0.42 & 103 & 250 & 2e + 38 \\
1339.058 & 1.46 & 29 & 250 & 4e + 38 \\
\end{align*}
\]

Notes.

$^a$ Time of the flare peak in BJD-2454833.
$^b$ Flare maximum in fractions of stellar flux.
$^c$ Duration of the rise (between the beginning and maximum) and decay (between the maximum and end) phase of the flare.
$^d$ Energy of the flare in white light (Kepler bandpass).

Figure 7. Distribution of $\Delta L_{\text{ave}}$ along morphology values. The red, green, blue, and magenta colors represent the distributions of detached, semi-detached, over-contact, and ellipsoidal binaries, respectively. The error bars represent the 1σ uncertainty in the AL calculations and the square root of the event numbers in each morphology-value bin.

Figure 6. Flare-number distributions and the light curve of KIC 11347875.

Mor becomes larger. When Mor > 0.7, two stars in a binary are so close and start sharing a common envelope, and the $\Delta L_{\text{ave}}$ variation starts becoming invisible in this condition. The $\Delta L_{\text{ave}}$ of over-contact binaries (Mor > 0.7) is depressed compared to those fast rotating detached binaries (Mor ∼ 0.5), which implies that the magnetic activity in common enveloped binaries may be frustrated by the development of the common envelope (Qian 2001, 2003). The error bars in Figure 7 represent the 1σ uncertainty in AL measurements and the square root of the $N_\text{f}$ number in each morphology-value bin (the method described in Figures 2 and 3 in Maehara et al. 2012). Maehara et al. (2012) studied superflares on solar-type stars with Kepler data, where they estimated that the uncertainties in luminosities and energies of flares are ±60%. We use the ±60% uncertainties in our work when calculating EW values in Equation (2), mainly for two reasons: (1) the duration times of most of the flares that we detected were comparable to those of superflares (typically a few hours), and the comparability may extend to stellar energy; and (2) it is impossible to calculate a reliable luminosity (or energy) uncertainty for binary systems because the reliability of all the essential parameters, such as effective temperature, surface gravity, and radius, are low because they are estimated by using the mixed light of a binary system.

3.3. The Effect of Orbital Period and Rotation

Orbital period ($P_{\text{orb}}$) is one of the most decisive parameters to influence the evolution of binary systems. We know that a shorter period usually refers to faster rotation due to tidal interaction (Walter & Bowyer 1981), and thus implies magnetic activity (Noyes et al. 1984). For instance, the RS CVn variables on which flares are observed are short period detached binaries with strong magnetic activity (Berdyugina & Järvinen 2005).

Figure 8(a) is the $\Delta L_{\text{ave}}$ variation along $P_{\text{orb}}$, which is extracted from the KEB catalog. $\Delta L_{\text{ave}}$ increases with shortening $P_{\text{orb}}$ up to a critical value at $P_{\text{orb}} \sim 3$ days, and thereafter the $\Delta L_{\text{ave}}$ strength decreases with decreasing $P_{\text{orb}}$. $\Delta L_{\text{ave}}$ shows no correlation with $P_{\text{orb}}$ when $P_{\text{orb}} > 35$ days. Figure 8(b) is the morphology distribution along the $P_{\text{orb}}$. All the contact systems (Mor > 0.7) shrink in a short orbital period range of $P_{\text{orb}} < 10$ days. Most of the binaries with $P_{\text{orb}} > 35$ days are quite detached systems shrinking in a narrow morphology range of Mor < 0.2.

The rotation rate of a star plays also an important role in the flaring rate (Nielsen et al. 2013). For instance, Notsu et al. (2013) and Shibayama et al. (2013) find that the flare frequency is lower in slowly rotating solar-type stars. For G, K, and M stars, Candelaresi et al. (2014) find that the flaring rate increases with rotation rate up to a critical value, and then the
flaring rate decreases linearly with increasing rotation rate. The same feature also applies to the binary systems. Figure 9(a) shows the $A_{\text{Lave}}$ variation along the rotation period ($P_{\text{rot}}$), where the $A_{\text{Lave}}$ increases with increasing rotation rate up to $P_{\text{rot}} \sim 1.5$ days, and then the $A_{\text{Lave}}$ starts decreasing with decreasing $P_{\text{rot}}$. In this work, $P_{\text{rot}}$ is only calculated for detached binaries. We follow studies such as Walkowicz et al. (2011), Maehara et al. (2012), and Nielsen et al. (2013), assuming that the period of brightness modulation corresponds to the rotation period of a star, and then we search the out-of-eclipse parts of binary light curves using the Lomb–Scargle periodogram to measure the stellar rotation period of the primary. We compute a Lomb–Scargle periodogram for each target in each quarter, and then we identify the peak of maximum power and record its period. The median value of the recorded periods of all the quarters is determined as the rotation period. Figure 9(b) shows the correlation between $P_{\text{orb}}$ and $P_{\text{rot}}$ for detached systems. The monotonically increasing correlation between two parameters stops at $P_{\text{rot}} \sim 32$ days.

3.4. Effect of Orbital Phase

It has been suggested that flares on active close binaries could arise due to magnetic reconnection field lines connecting two components (Simon et al. 1980; van den Oord 1988; Gunn et al. 1997), for instance, tidal effect can play an important role for the enhanced magnetic activities in RS CVn stars (Cuntz et al. 2000). Because the gravitational interaction and mass transfer between two stars may break the spherical symmetry of stars and influence the development of magnetic fields, the density of magnetic field lines around the binary could relate distribution to orbital phase (Holzwarth & Schüssler 2003a, 2003b), and thus the flaring rate may be also sensitive to the orbital phase. Geometrically, a binary system presents its largest cross section on the line of sight at the orbital phases 0.25 and 0.75 (primary eclipse at phase 0). If the magnetic activity is randomly distributed on the surface of both components, the $N_{\text{f}}$ distribution should be modified simply due to the eclipse, i.e., the $N_{\text{f}}$ minimum at phase 0 and 0.5, and the flat $N_{\text{f}}$ distribution at other phases; and meanwhile, any “peculiar” $N_{\text{f}}$ distribution would indicate the different magnetic features or different magnetic activity areas.

KIC 2309587 is a detached binary with $N_{\text{f}} = 128$ (Table 1), $T_1 = 5166$ K, and $T_2 = 5577$ K (Armstrong et al. 2014). The value of $\log g = 4.326$ (from revised KIC, Huber et al. 2014) indicates that both components are main-sequence stars. It is selected as an example for detecting the correlation between the
flaring rate and the orbital phase in the detached system. The amplitude-weighted flare number distribution \(N'_f\) (top panel), flare number distribution \(N_f\) (middle panel), and orbital-phase folded light curves \(\Delta F/F\) (bottom panel) of the binary are presented in Figure 10(a), respectively. The symmetric light curve in the bottom panel indicates the non-existence of large star-spots. Both \(N'_f\) and \(N_f\) drop at phase 0 and 0.5, and keep almost constant at other phases, which indicates that flares are more likely to originate from both components in the system, and the flaring rate is irrelevant to the orbital phase.

Figure 10(b) is the same as Figure 10(a), but for KIC 11457191, which is a semi-detached binary with 210 flares detected (Table 1). The revised KEB catalog shows that the system has \(T_{\text{eff}} = 5858\) K, \(\log g = 4.486\), and an orbital period of \(P_{\text{orb}} = 2.298\) days. The flare-number-distribution variation of the binary is still dominated by the eclipse between the two components. As mass transfer begins in the system, and \(N_f\) keeps roughly flat at phase >0.5, flaring should be more active on the obtaining-mass secondary, but still, no sign of the correlation between magnetic activity and orbital phase is presented in Figure 10(b).

We use 20 non-eclipse binaries with Mor > 0.7 to examine the correlation. In total, 203 flares are distributed along the orbital phase in Figures 11(a) and (b). Figure 11(c) gives the orbital-period folded light curve of KIC 11153627 as an example to illustrate the typical baseline flux variation of an ellipsoidal system. In both Figures 11(a) and (b), the significant enhancement of flare numbers amazingly shows up at around phases 0.25 and 0.75, which is consistent with the positions of the largest amplitudes in Figure 11(c). We know that even for the non-eclipse binaries, the cross section on the line of sight still varies with orbital phase due to tidal distortion, and so does the surface luminosity; therefore, the maximum light-curve amplitude of each binary can be viewed as the upper limit of the cross section discrepancy, which is approximately 12% for KIC 11153627 (as shown in Figure 11(c)); in other words, the changes of the cross section should be no more than 12% for the binary.

The averaged cross section variation for the 20 non-eclipse samples is actually 2.9% ± 2.6%. 2.6% is the 1σ deviation, and thus the 12% can be approximately considered as the upper limit of the cross section modification. In order to investigate how essential the cross section is to the flare detection, we assume that the minimum cross section of a binary is 1 at phases 0 and 1, and the maximum cross section is 1.12 at
phases 0.25 and 0.75, because the maximum cross section variation is 12\%, and then we calculate the flare numbers again by dividing the numbers with the corresponding cross section area. The red dashed line and the black solid line in Figure 11 present flare number distributions with and without cross section correction, respectively, and both lines in the $N_f^*$ and $N_f$ distributions in Figure 11 show clear enhancement at phases 0.25 and 0.75. Such variation can be larger than what is expected from the difference of the cross sections between phase 0.25(0.75) and phase 0(1).

Figure 12. Light curves of each flare detected on KIC 001575690. The horizontal and vertical axes correspond to the time (days) from the flare, and the relative flux ($\Delta F/F$), respectively. In each panel, the black, green, and red lines present the light curves of the observed data, the baseline fitting flux, and the flares, respectively. The modified Julian date (MJD) of the flare peak time ($t_0$) is given on the top of each panel. (The complete figure set (235 images) is available online.)
4. DISCUSSION AND CONCLUSION

In this paper, we present the results of flare-binary identification from Kepler LC data. We identify 234 flare binaries out of the 1049 binary samples in the KEB catalog. We use a 4-terms Fourier series to capture flare features, and finally 6818 flares are detected on the 234 flare binaries.

We pay special attention to a triple system, KIC 5952403, also known as HD 181068. Previous studies argue that flares on the system should be generated simply on the inner pair (Derekas et al. 2011) or simply on the outer giant (Czesla et al. 2014). By estimating the necessary hemisphere coverage according to the observed flare peak luminosity, we confirm that the 19 flares detected in this work from the Kepler LC light curve should originate on the giant star.

We compare the flare-binary fraction in binaries of different morphology types. The result shows that the fractions in overcontact and ellipsoidal binaries are approximately 10%-20% lower than those in detached and semi-detached systems. Contact binaries are usually more luminous compared to detached ones, and high luminosity naturally decreases the visibility of flare events, which the 10%-20% difference should be mainly attributed to. In addition, the existence of common envelopes in contact systems may depress the activity of the magnetic field and thus influence flare generation.

We identify a parameter named “AL” (Equation (3)) to estimate the ratio of flare energy over the baseline energy in a binary. We discuss the ALave variations along the Porb and Prot (calculated for only detached binaries) parameters. We report that ALave increases with decreasing Porb and/or Prot up to critical values at Porb ~ 3 days or Prot ~ 1.5 days; thereafter, the ALave starts decreasing no matter how fast the stars rotate. When considering the ALave variation in different morphology types, we find that the variation is related to the interacting activities between two stars in a binary. As presented in Figure 8, when Mor > 0.5, meaning at least one of the components has filled its Roche lobe and mass transfer begins, ALave starts decreasing with increasing Mor; when Mor > 0.7, meaning that the two stars in a binary are close and start sharing a common envelope, and ALave variation starts becoming invisible under this condition.

We examine the flaring rate as a function of orbital phase in two eclipsing binaries for which a large number of flares are detected. It appears that there is no correlation between flaring rate and orbital phase in these two binaries. In contrast, when we examine the function with 203 flares on 20 non-eclipse ellipsoidal binaries, bimodal distributions of both Nf1 and Nf2 show up at orbital phases 0.25 and 0.75. We argue that the maximum 12% cross section variation cannot afford the observed flare-number difference between phase 0.25(0.75) and 0(0.5), as presented in Figures 11(a) and (b). We conclude that the bimodal distribution might be still related to the slight orbital inclination and/or gravitational distortion, and meanwhile, such variation can be larger than what is expected from the difference of the cross sections between phase 0.25(0.75) and phase 0(1).

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APPENDIX

FLARE ATLAS

An example light curve from the 6818 flares is shown in Figure 12 for KIC 001575690.

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