Flare Properties of A-type Stars in Kepler Data

Jian-Ying Bai¹,² and Ali Esamdin¹

¹ Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, People’s Republic of China; aliyi@xao.ac.cn
² University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China

Received 2020 August 12; revised 2020 October 18; accepted 2020 October 21; published 2020 December 18

Abstract

We analyzed the long-cadence (LC) light curves of 5435 stars with effective temperatures of 7000–10,500 K in Data Release 25 of Kepler to extend the samples of A-type flare stars and study their flare properties. A total of 103 flare stars are detected, of which 72 have the Large Sky Area Multi-Object fiber Spectroscopic Telescope spectral types, resulting in 51 A-type stars, including 17 new and 34 known. A total of 352 flares are detected from the 51 stars. The flare durations, amplitudes, and energies in the Kepler band are calculated, with medians of 2.5 hr, 2.1 mmag, and $10^{35.8}$ erg, respectively. We give the flare frequency distribution (FFD) of the A-type stars. Within the same energy range, the flare rates of our FFD are lower than those in previous research, which was also based on Kepler LC data, and the FFD slope is consistent with that in the research. The activity–rotation relation of the A-type flare stars is shown for the first time, in which the flare activity decreases as the rotation period increases. The relation is similar to that of the late-type stars in previous studies. For the two relatively bright A-type flare stars, KIC 5360548 and KIC 9468475, three high-resolution spectra are observed on different nights for each of them, and radial velocities are calculated and compared with that of the previous research. The comparisons suggest that there is no evidence of the KIC 5360548 companion, and KIC 9468475 could have a low-mass companion.

Unified Astronomy Thesaurus concepts: Stellar flares (1603); Optical flares (1166); Early-type stars (430); A stars (5); Catalogs (205)

1. Introduction

A flare was first detected on the Sun in 1859 (Carrington 1859; Hodgson 1859), which was due to energy release of the magnetic reconnection that occurred in the outer atmosphere, with emissions from X-rays to radio wavelength (Benz & Güdel 2010; Charbonneau 2010; Osten et al. 2010; Davenport et al. 2012). Stellar flares are usually detected in late-type stars, generally in dMe stars (Gershberg 1989; Audard et al. 2000; Gershberg 2005; Yang et al. 2017; Froning et al. 2019; Yang & Liu 2019). Their precise mechanism is not yet known, but it is commonly considered that their energies are generated from a magnetic field like a solar flare (Benz & Güdel 2010; Charbonneau 2010).

Late-type stars have sufficiently deep convective envelopes to generate strong magnetic fields, which leads to flares. In early-type stars, the convective envelopes are too shallow to produce flares through the known dynamo mechanism as in the Sun (e.g., Charbonneau 2010). Rosner & Vaiana (1980) suggest that the dynamo-generated magnetic fields occur at the spectral type later than F5.

A-type stars are not expected to generate flares. However, flare events associated with the stars are reported in the U band, extreme ultraviolet, and X-ray (Wang 1993; Schmitt et al. 1994; Mullan & Mathioudakis 2000). Recently, more than 100 A-type flare stars have been detected in Kepler (Balona 2012, 2013, 2015; Van Doorsselaere et al. 2017; Yang & Liu 2019) and TESS data (Balona 2020), although the underlying mechanism of flaring is unclear (Pedersen et al. 2017). More A-type flare stars are needed to improve our understanding of their flare properties and origin.

In this paper, we analyze the long-cadence light curves of 5435 stars with effective temperatures ranging from 7000 to 10,500 K in Data Release 25 of Kepler. The spectra types of the detected flare stars are obtained from the Large Sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST) DR5 catalog in order to identify A-type ones. This paper is organized as follows. In Section 2, the Kepler data used in this paper are described. In Section 3, data analyses are presented. Results are given in Section 4. Discussions are outlined in Section 5 and in the final section, Section 6, we give a summary.

2. The Kepler Data

The Kepler satellite was launched in 2009 March by NASA. Its main goal is to search for Earth-size planets in the extended solar neighborhood with a field of view (FOV) of 105 deg² (Borucki et al. 2010; Koch et al. 2010). The precision of Kepler approaches 10 and 100 ppm for bright ($V = 9–10$ mag) and faint stars ($V = 13–14$ mag), respectively. Kepler has two sampling modes, long cadence (LC) and short cadence (SC). The integration time of LC is 29.4 minutes and that of SC is 1 minute (Gilliland et al. 2010; Jenkins et al. 2010a, 2010b).

The lifetime of the Kepler mission contains two stages. The first stage (K1) lasts from 2009 to 2013, during which Kepler continuously pointed at a single star field in the Cygnus-Lyra region, and the second (K2) from 2014 to 2018, during which it observed around the ecliptic plane due to the trouble of the reaction wheels of the telescope. K1 provides continuous data of $\sim200,000$ stars for a relatively long duration (∼four years) and the data quality is better than that of K2 (Van Cleve et al. 2016; Ilin et al. 2019). The LC data in K1 are applied in this work.

Kepler provides the Simple Aperture Photometry (SAP) and Pre-search Data Conditioning (PDC) flux. In the PDC data, flares may be mistaken and removed as outliers, and therefore the SAP data are applied in this study as done in previous research (Balona 2015; Davenport 2016; Yang et al. 2017; Yang & Liu 2019). Kepler data are publicly available on the
Kepler Asteroseismic Science Operations Center (KASOC) homepage.3

A sample of 5435 stars with effective temperatures ranging from 7000 to 10,500 K is selected from Kepler Data Release 25 (DR 25) whose details can be found in Mathur et al. (2017). In the Kepler Input Catalog (KIC), the effective temperatures of the hotter stars are not reliable due to the lack of observations in the UV (Brown et al. 2011; Balona 2012; Pinsonneault et al. 2012). In this work, the range of 7000–10,500 K is only used to roughly select the stars with spectral types of A9 to A0 (Gray & Corbally 2009).

3. Data Analysis

3.1. Flare Detection

A program is written to automatically detect flares from the light curve of each quarter for each star in our sample. Three processing steps are applied in the program. For the first step, the light curve from a quarter (Raw LC) is fitted iteratively by smoothing average to exclude outliers in order to obtain a quiescent phase (Hawley et al. 2014; Davenport et al. 2016; Yang et al. 2017; Yang & Liu 2019). A moving average filter is applied in the smoothing and we select the bandwidth of 11 to obtain a better smoothing of the quiescence in a light curve. The mean and standard deviation (SD) of every 100 points in the quiescence are calculated, and outliers are excluded when they are beyond the range of the mean plus or minus twice the SD. In the second step, the quiescent phase is fitted by smoothing average, and then the Raw LC is subtracted by the fitting line to get a subtracted light curve (Residual LC). In the final step, every 100 data points in the Residual LC are checked to obtain flare candidates with the similar criteria used in previous studies (Hilton et al. 2011; Hunt-Walker et al. 2012; Hawley et al. 2014; see our Figure 1). The criteria are as follows: (1) There are at least three consecutive measurements in a flare light curve; (2) the measurements are more than two times the SD of the quiescent phase and at least one of them is higher than four times the SD. Beside the criteria, the flare profile is also checked through a graphic interface to confirm that the profile consists of a repaid rise (relatively short) and an slow decay (relatively long). A sample of flare light curves is shown in Figure 2.

After analyzing the LC light curves of 5435 stars, all the detected flares are checked in order to exclude the ones that appeared on different stars within a window of 0.1 d, which are considered as an instrumental effect (Balona 2012, 2013; Pedersen et al. 2017).

3.2. Contamination Check

Contamination is defined as the light in the photometric aperture of an object that does not actually originate from that

---

Figure 1. The Raw LC and Residual LC of KIC 12072819 in Quarter 2. They are marked with black points. In the top panel, the thick gray line presents the smoothing average of the quiescent phase. In the bottom panel, the two black lines indicate the positions of two (lower) and four times (higher) the SD of every 100 data points in the Residual LC, respectively. The arrow shows one identified flare. The insert in the bottom panel is the zoom-in of the flare. The horizontal axis is the Barycentric Reduced Julian Date (BRJD or BJD–2400000) and the vertical is the Kepler flux in parts per thousand (ppt).

Figure 2. A sample of flare light curves from the new A-type flare stars. In each panel, the two black lines indicate the positions of two (lower) and four times (higher) the SD of the quiescence, respectively. KIC number is indicated in each panel. The horizontal axis is the time in hours since the start of each flare.

---

3 https://kasoc.phys.au.dk/
The identified A-type flare stars in Section 3.1 are probably contaminated by nearby objects. We exclude the flare stars with possible contamination by the procedures below:

1. The Kepler eclipsing binary catalog\(^4\) (KEB) includes about 2900 binary stars. They are excluded from the A-type flare stars as done in previous studies (Yang et al. 2017; Yang & Liu 2019). The Simbad catalog\(^5\) is also used to exclude the eclipsing binary.

2. The typical photometry apertures of Kepler targets are determined as a radius of 16\(^{\prime\prime}\)–28\(^{\prime\prime}\) (4–7 pixels) given the pixel scale of Kepler CCD (3\(^{\prime\prime}\)98 × 3\(^{\prime\prime}\)98) (Bryson et al. 2010; Van Cleve & Caldwell 2016). By using the interactive Aladin Sky Atlas\(^6\) (Bonnarel et al. 2000; Boch & Fernique 2014), the A-type targets with field stars located within 12\(^{\prime\prime}\) are excluded (Shibayama et al. 2013; Yang et al. 2017).

3. A Kepler mask consists of the optimal selection of pixels for a target that maximizes the signal-to-noise ratio (S/N) when the pixel flux is combined (Bryson et al. 2010; Pedersen et al. 2017). An aperture mask consists of the pixels in and around the Kepler mask. For each of the A-type stars, we plot its flare light curves from the pixels within its aperture mask as done in Pedersen et al. (2017). Figure 3 shows the flare light curves within the aperture mask of KIC 11046028. A flare event is excluded if its peak appears outside the Kepler mask.

|   | 1 | 1 | 1 | 1 | 3 | 1 |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 3 | 9 | 12 | 4 |
| 1 | 1 | 1 | 9 | 21 | 9 | 6 |
| 5 | 2 | 7 | 21 | 31 | 5 | 1 |
| 1 | 1 | 11 | 20 | 9 | 1 |
| 5 | 1 | 6 | 34 | 2 |
| 1 | 1 | 3 | 14 | 3 |

**Figure 3.** The flare light curve vs. time in each pixel within the aperture mask of KIC 11046028. In each curve, the quiescent phase is indicated by gray points and the flux in the flare duration is shown with open circles. The S/N of the flux in the flare duration is indicated on the top of each light curve. The Kepler mask is marked with a thick black border. All the light curves are shown in the same flux scale. The blank pixels are not used in Kepler.

|   |   |   |   |   |   |
|---|---|---|---|---|
|   |   |   |   |   |

**Figure 4.** A sample of LAMOST spectra for the A-type stars in this paper. Each spectrum is normalized to its maximum and added with a constant to improve readability. KIC number and spectral type are indicated on the top of each spectrum.

### 3.3. Spectral Classification

The spectral types of the flare stars are obtained from the LAMOST DR5 catalog (Luo et al. 2019) in order to identify A-type ones. The spectra of these stars can be obtained from the official website of LAMOST (www.lamost.org). They have a resolution of \(R = \sim 1800\) and a wavelength range from 370 to 900 nm (Cui et al. 2012; Zhao et al. 2012). The details of LAMOST can be found in Wang et al. (1996) and Xing et al. 3

---

\(^4\) [http://keplerebs.villanova.edu/](http://keplerebs.villanova.edu/)

\(^5\) [http://simbad.u-strasbg.fr/simbad/](http://simbad.u-strasbg.fr/simbad/)

\(^6\) [https://aladin.u-strasbg.fr/AladinLite/](https://aladin.u-strasbg.fr/AladinLite/)
Table 1
Parameters of the New A-type Flare Stars

| KIC No. | Teff (K) | Kp (R☉) | Distance (kpc) | Pout (day) | Spectra Type | log LKp (erg s⁻¹) | Nf | Comment |
|---------|---------|---------|----------------|------------|--------------|-----------------|----|---------|
| 1128905 | 7305    | 1.43    | 1.0 ± 0.03     | 0.9 ± 0.0095 | A7           | 34.4 ± 0.02     | 1  |         |
| 8547366 | 7976    | 2.42    | 0.7 ± 0.01     | 0.6 ± 0.0056 | A7           | 35.0 ± 0.01     | 2  |         |
| 598837  | 8105    | 2.01    | 0.5 ± 0.01     | 0.7 ± 0.0005 | A6           | 34.8 ± 0.01     | 4  |         |
| 7899920 | 8152    | 1.86    | 1.0 ± 0.02     | 0.9 ± 0.0005 | A6           | 34.2 ± 0.02     | 8  |         |
| 12072819| 7904    | 1.70    | 2.0 ± 0.07     | 44.9 ± 0.0918| A7           | 35.3 ± 0.03     | 1  |         |
| 9666597 | 8283    | 3.12    | 3.8 ± 0.56     | 2.5 ± 0.0918 | A5           | 35.3 ± 0.14     | 1  | Am star |
| 5615282 | 8392    | 2.66    | -              | 1.7 ± 0.0059 | A5           | -               | 1  |         |
| 9472363 | 8413    | 2.99    | 1.1 ± 0.03     | 12.9 ± 0.6345| A7           | 34.9 ± 0.02     | 1  |         |
| 5615282 | 8338    | 2.35    | 0.8 ± 0.02     | 0.7 ± 0.0039 | A5           | 34.8 ± 0.02     | 3  |         |
| 9468475 | 8607    | 7.6     | 0.1 ± 0.00     | 13.5 ± 0.2454| A6           | 34.9 ± 0.03     | 1  |         |
| 11189284| 8867    | 3.83    | 1.4 ± 0.05     | 2.4 ± 0.0070 | A6           | 35.3 ± 0.02     | 1  |         |
| 5360548 | 8645    | 10.0    | 0.4 ± 0.01     | 0.5 ± 0.0008 | A2           | 34.9 ± 0.02     | 6  |         |
| 11046028| 8319    | 12.2    | 3.22           | 11.7 ± 0.4247| A1           | 34.8 ± 0.03     | 2  |         |
| 6515722 | 9174    | 11.7    | 2.47           | 1.3 ± 0.05   | A2           | 35.1 ± 0.04     | 4  |         |
| 1872324 | 9534    | 9.9     | 2.06           | 0.5 ± 0.01   | A1           | 35.0 ± 0.01     | 2  |         |
| 5721628 | 7758    | 13.1    | 1.40           | 1.2 ± 0.02   | A7           | 34.5 ± 0.02     | 4  |         |
| 6134228 | 8224    | 13.9    | 1.60           | 2.1 ± 0.0036 | A1           | 34.4 ± 0.03     | 1  |         |

Note. Effective temperature, Teff and Kepler magnitude, Kp are from the KIC. For the star radius (R), a given by Gaia Collaboration et al. (2018) and the others are from the KIC. Distance is from Gaia Collaboration et al. (2018). The symbol ± indicates the distance is not given in Gaia Collaboration et al. (2018). Pout is the rotation period of each star (given by Reinhold et al. 2013; the others are given by this work). Spectra types are from Luo et al. (2019). Luminosity of each star, log LKp (the symbol ± indicates the luminosity is not calculated without distance), and flare number, Nf, are obtained by this work. The special star is marked in the last column according to the Simbad homepage.

Figure 5. The histograms of the effective temperature for the 5435 stars (top panel) and 51 A-type flare stars (bottom panel).

Figure 6. The positions of the 51 A-type flare stars in the H-R diagram. Gray dots indicate Kepler stars in the range of 7000 to 11,000 k (Mathur et al. 2017). The known 34 and new 17 A-type ones are indicated by black dots and plus symbols, respectively. The luminosity of the stars are calculated by effective temperatures and radius from KIC.

Gershberg 1972; Hunt-Walker et al. 2012; Hawley et al. 2014). The Kepler-band flux for each A-type flare star is determined, given the Kepler zero-point magnitude of −20.24 (Hawley et al. 2014) and Kepler magnitude of the star. The LKp for each A-type flare star is calculated with 4πd² multiplied by the Kepler-band flux, where d is the distance from the star to the Earth (Gaia Collaboration et al. 2018). The LKp of each star is listed in Tables 1 and 2. The Kepler-band flare energies of the new A-type stars are shown in Table 3.

3.4. Energy Estimate

Following the method applied in Hawley et al. (2014), the flare energy (EKp) of a Kepler star is computed with the equivalent duration (EW; Gershberg 1972) of the flare multiplied by the quiescent luminosity (LKp) of the star. The EW is defined as the amount of the time that the star would take in its quiescent state to release the same amount of energy released during a flare, and is calculated as the time integral of Ff(t)/F0, where Ff(t) is the flux of the flare and F0 is the flux of the star in the quiescent state (see
of the A-type star released in the whole observation time. The rotation periods
are obtained from Reinhold et al. (2013; 2014) and Yang & Liu (2019). And, for the
stars without rotation periods in previous research, we compute
the periods by the Lomb–Scargle algorithm (Reinhold et al. 2013; McQuillan et al. 2014; Yang & Liu 2019). The correlation coefficients of FA versus rotation period, effective temperature,
and radius are computed for the A-type flare stars. Figure 9 presents the distribution of FA and each of the three star parameters. Following the method applied in Rebull et al. (2016), the amplitude of the rotational modulation from the light curve in Q3 is estimated for each A-type flare star, providing a rough indication of the approximate area of the starspot. Figure 10 shows the distribution of the amplitudes and rotation periods.

3.5. Radial Velocity (RV) Estimate

High-resolution spectra for the two relatively bright A-type flare stars (KIC 9468475 and KIC 5360548) are observed by using a 2.16 m telescope. The telescope is located at the Xinglong station of the National Astronomical Observatories of China. A Fiber-fed High Resolution Spectrograph (HRS) is mounted on the telescope. The HRS has a CCD of 4096 × 4096 pixels. Its wavelength coverage is from 3300 to 10000 Å, and the resolution power is from 32,000 to 106,000. The limiting magnitude could reach $V = 9.5$ in the red band and $V = 7.2$ mag in the blue band with S/N = 100 for one hour of exposure (Zhao et al. 2000; Zhao & Li 2001). More parameters of the telescope and HRS can be found in Fan et al. (2016).

For each of the two stars, three spectra are obtained on different nights (Table 4), and reduced by the IRAF packages. Following the method in Pedersen et al. (2017), RVs of a star are determined through cross-correlation of each spectral order of the star’s spectrum with a synthetic template spectrum. The template spectrum is calculated using the stellar spectral synthesis program SPECTRUM (Gray & Corbally 1994) and Kurucz model atmospheres (Castelli & Kurucz 2003). For both stars, the Kurucz model atmospheres with effective temperatures $T_{\text{eff}} = 8500$ K, log $g = 4$, [M/H] = 0, $\xi = 2$ km s$^{-1}$ are used. The spectral orders with telluric or Balmer lines are excluded. RVs are calculated with the remaining orders and averaged as a final RV. The error of the final RV is estimated as error = $\sigma/\sqrt{n}$, where $\sigma$ is the SD of the RVs and $n$ is the number of the used spectral orders (Hunt-Walker et al. 2012; Pedersen et al. 2017). Table 4 shows the RVs of the two stars.

4. Results

Through the method described in Sections 3.1 and 3.2, a total of 103 flare stars are identified with 17 contaminated removed. Among them, 72 have LAMOST spectral types, leading to 51...
Figure 9. Flare activity (FA) vs. rotation period (left panel), effective temperature (middle panel) and star radius (right panel) of the A-type flare stars. In all the panels, the vertical lines indicate one standard deviation error of the FA. In each panel, the horizontal lines show 1σ error of each star parameter.

Figure 10. The amplitude of the periodic light curve vs. rotation period. The vertical lines indicate 1σ photometric error and the horizontal show 1σ error of the rotation period for each star.

Table 4
| KIC No. | Date       | Exposure Time (s) | RV (km s⁻¹) | N_counts |
|---------|------------|-------------------|-------------|----------|
| 5360548 | 2019 Nov 7 | 2300              | −48.3 ± 64.1| 6        |
| 5360548 | 2019 Nov 10| 2400              | −38.5 ± 28.6| 4        |
| 5360548 | 2019 Dec 3 | 2300              | −37.7 ± 11.7| 4        |
| 5360548 | 2019 Dec 6 | 600               | −21.9 ± 35* |          |
| 9468475 | 2019 Oct 15| 1200              | −2.9 ± 5.5  | 8        |
| 9468475 | 2019 Dec 4 | 600               | −8.5 ± 10.4 | 8        |
| 9468475 | 2019 Dec 6 | 600               | −10.7 ± 4.1 | 8        |
| 9468475 | 2019 Dec 7 | 600               | −23.0 ± 4.5 |          |

Note. For RV, a is given by Frasca et al. (2016) and the others are given by this work.

A-type flare stars, which consist of 17 new and 34 known. The A-type flare stars in this work refer to the flare stars with spectral types of A, which include both normal and special (e.g., Am type). Table 1 shows the parameters of the 17 new A-type flare stars, including KIC number, Kepler magnitude, and radius from KIC, the distance given by Gaia Collaboration et al. (2018), rotation period given by previous research and this work, the spectral type from LAMOST, the luminosity in log, flare count, and comment. Table 2 is same as Table 1, except it lists the parameters of the 34 known. Figure 5 shows the histograms of the effective temperatures for the 5345 stars and 51 A-type ones.

A total of 352 flares are detected from the 51 A-type stars. Table 3 shows the parameters of the 43 flares detected from the 17 new, including the flare number, the KIC number, the peak time of each flare in BRJD, the duration in hours, the EW in seconds, the peak in mmag, and the Kepler-band flare energy in log. Figure 7 presents the histograms of the flare durations, amplitudes, and energies, with the median values of 2.5 h, 2.1 mmag, and 10^{35.8} erg, respectively. The range of the Kepler-band energies is from 10^{34.2} to 10^{37.5} erg. The FFD of the 51 stars is shown in Figure 8, and is fitted by the least-squares power law of log(dN/dE) = −1.26±0.56 log(E_{Kp}) + 10.52±4.71. Following the method of maximum likelihood applied in Gizis et al. (2017), the slope (1.23±0.18) of the FFD is also estimated with unbinned data in the range of 10^{35.5}–10^{38.5} erg. Figure 9 illustrates the distributions of the flare activity versus rotation period, effective temperature, and radius for the 51 A-type flare stars, with the correlation coefficients of −0.31, 0.04, and −0.02, respectively. Their p values are 0.03, 0.79, and 0.90, respectively. Figure 10 also gives the relation of the amplitudes of periodicity versus rotation periods for all the A-type flare stars, with the correlation coefficient of −0.19 and p value of 0.2. The RVs of KIC 9468475 and KIC 5360548 are shown in Table 4, which includes KIC number, the observation date of each spectrum, the exposure time in seconds, the RV in km s⁻¹, and the number of the spectral orders used. Figure 11 shows a sample of the spectra used for estimating RV for KIC 9468475. We note that the spectral noise is large and the errors of the RVs are big.

5. Discussion

A-type flare stars are first detected in LC data of the Kepler mission in Balona (2012). So far, the number of the stars reported by previous studies has reached more than 100 (see Balona 2012, 2013, 2015, 2020; Van Doorsselaere et al. 2017; Yang & Liu 2019). In this work, we analyze the LC light curves of 5435 stars with effective temperatures of 7000–10,500 K from Kepler DR 25, resulting in 51 A-type flare stars, which consist of 17 new and 34 known. The number
of A-type flare stars detected in this study is different from those in previous research using Kepler data (e.g., Balona 2012, 2013, 2015; Van Doornsselaere et al. 2017; Yang & Liu 2019). The main cause could be the different threshold on the amplitude applied in our work.

In Yang & Liu (2019), the authors give an FFD of 37 A-type flare stars (583 flares) detected in Kepler LC data. The FFD is fitted in the energy range of $10^{35.5}$ and $10^{36}$ erg and its slope is $1.12 \pm 0.08$. The flare rates ($dN/dE$) in the FFD are $1.7 \times 10^{-34}$ yr$^{-1}$ and $1.5 \times 10^{-35}$ yr$^{-1}$ at $10^{35}$ and $10^{36}$ erg, respectively. In this work, the FFD of the 51 A-type flare stars (352 flares) is given and fitted in the energy range of $10^{35.5}$ and $10^{36}$ erg. The flare rates in our FFD are $7.5 \times 10^{-35}$ yr$^{-1}$ and $10^{-35}$ yr$^{-1}$ at $10^{35.5}$ and $10^{36}$ erg, respectively. The FFD slope is $0.98 \pm 0.28$. Within the same energy range ($10^{35.5} - 10^{36}$ erg), the flare rates of our FFD are 0.3–0.6 times lower than that of the FFD in Yang & Liu (2019), which is likely due to the fewer flare samples in this paper. In addition, our FFD slope is consistent with that in Yang & Liu (2019). The FFD slope significantly deviates from that of the cooler stars (F- to M-type stars), which may mean the superflares on A-type stars occur in a different way (e.g., Yang & Liu 2019). Svanda & Karlický (2016) also gives an FFD of 12 A-type flare stars (28 flares) detected in Kepler SC data. The FFD is fitted in the energy range of $10^{34.1} - 10^{36.5}$ erg and the slope is $1.37 \pm 0.07$ which is consistent with ours. The flare rates ($dN/dE$) in the FFD are $10^{-35.8}$ yr$^{-1}$ and $10^{-37}$ yr$^{-1}$ at $10^{35.5}$ and $10^{36}$ erg, respectively. Within the similar energy range, the flare rates of our FFD are 50–60 times higher than that of the FFD in Svanda & Karlický (2016), which is possibly due to the fewer flare samples in that paper.

In Figure 9, the left panel shows the activity–rotation relation of the 51 A-type flare stars, with the correlation coefficient of $-0.31$ and $p$ values of 0.03. This result suggests a trend that the flare activity increases as the rotation period decreases. The similar results are reported for late-type stars (G/K/M type) in previous research (see Wright et al. 2011; Yang et al. 2017; Notsu et al. 2019; Yang & Liu 2019). It is considered that the interaction between stellar rotation and convection can generate a magnetic field, which is an important factor for flare activity (Parker 1955). Weak magnetic field ($\sim 1$ G) is reported on a normal A-type star, Vega (A0) (Lignières et al. 2009). In this work, the activity–rotation relation indicates that the magnetic fields of A-type flare stars could be strengthened by faster rotation, leading to higher flare activity. Figure 10 illustrates the distribution between the amplitudes and rotation periods for the 51 A-type flare stars, with the correlation coefficient of $-0.19$ and $p$ value of 0.2. The result indicates a decreasing trend between spot activity and rotation period, which supports the hypothesis that flares are related to the spots. In Balona (2012, 2015), the author argued that the flare in the energy scale of $10^{36} - 10^{37}$ erg cannot be explained by the flare scale of low-mass companions. This indicates that the observed superflares on A-type stars do not occur on the low-mass companion (G/K/M-type stars).

For the second relatively bright A-type flare stars, KIC 5360548 and KIC 9468475, their RVs ($-21.9 \pm 35$ and $-23.0 \pm 4.5$) are given by Frasca et al. (2016), and also shown in Table 4. For KIC 5360548, the RV is roughly the same as that obtained in our work. For KIC 9468475, its RV is significant different from that in this study.

6. Summary

We analyzed the LC light curves of 5435 stars with effective temperatures from 7000 to 10,500 K in the Kepler data to find more A-type flare stars and study their flare properties. A total of 103 flare stars are obtained, of which 72 have spectral types from the LAOMST DR5 catalog, resulting in 51 A-type flare stars, which consist of 17 new and 34 known. A total of 352 flares are detected from the A-type flare stars. The flare durations, amplitudes, and energies of the Kepler band are also obtained, whose median values are 2.5 hr, 2.1 mmag, and $10^{35.8}$ erg, respectively. The FFD of the A-type stars is given and fitted by the least-squares power law of $\log(dN/dE) = -1.26 \pm 0.56 \log(E_{kp}) + 10.52 \pm 1.71$. Within the energy range of $10^{35} - 10^{36}$ erg, we compare the FFD in this paper with that of 37 A-type flare stars in previous research, which is also based on Kepler LC data. The flare rates of our FFD are 0.3–0.6 times lower than that in the previous study, and the two FFD slopes ($1.26 \pm 0.56$ and $1.12 \pm 0.08$) are consistent. The activity–rotation relation of the A-type stars suggests a trend that the flare activity decreases as the rotation period increases. This relation is similar with that of the late-type stars in previous research. High-resolution spectra are observed on different nights for each of the two relatively bright stars (KIC 5360548 and KIC 9468475) and used to calculate RVs. The calculated RVs are also compared with that from previous research. We could not find any evidence of KIC 5360548’s companion, but found that KIC 9468475 could have a low-mass companion.

The authors thank the referee for the very helpful comments and the editor for the careful revision of the manuscript. This research is supported by the National Natural Science Foundation of China under grants No. 11873081 and No. U2031209. We thank the Kepler science team for providing such excellent data. We acknowledge the support of the staff of the Xinglong 2.16 m telescope.

Appendix

We present the pixel level data of KIC 5360548 in Figure 12, which shows the flare light curve in each pixel within the aperture mask of the star.
References

Audard, M., Güdel, M., Drake, J. J., et al. 2000, ApJ, 541, 396
Balona, L. A. 2012, MNRAS, 423, 3420
Balona, L. A. 2013, MNRAS, 431, 2240
Balona, L. A. 2015, MNRAS, 447, 2714
Balona, L. A. 2020, arXiv:2008.06305
Benz, A. O., & Güdel, M. 2010, ARA&A, 48, 241
Boch, T., & Fernique, P. 2014, in ASP Conf. Ser. 485, Astronomical Data Analysis Software and Systems XXIII, ed. N. Manset & P. Forshay (San Francisco, CA: ASP), 277
Bonnetel, F., Fernique, P., Bienaymé, O., et al. 2000, A&AS, 143, 33
Bonucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Brown, T. M., Latham, D. W., Everett, M. E., et al. 2011, AJ, 142, 112
Bryson, S. T., Jenkins, J. M., Klaus, T. C., et al. 2010, Proc. SPIE, 7740, 77401D
Carrington, R. C. 1859, MNRAS, 20, 13
Castelli, F., & Kurucz, R. L. 2003, in IAU Symp. 210, Modelling of Stellar Atmospheres, ed. N. Piskunov, W. W. Weiss, & D. F. Gray (San Francisco, CA: ASP), A20
Charbonneau, P. 2010, LRSP, 7, 3
Coughlin, J. L., Thompson, S. E., Bryson, S. T., et al. 2014, AJ, 147, 119
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 1979
Davenport, J. R. A. 2016, ApJ, 829, 23
Davenport, J. R. A., Becker, A. C., Kowalski, A. F., et al. 2012, ApJ, 748, 58
Davenport, J. R. A., Kipping, D. M., Sasselov, D., et al. 2016, ApJL, 829, L31
Fan, Z., Wang, H., Jiang, X., et al. 2016, PASP, 128, 115005
Frasca, A., Molenda-Żakowicz, J., De Cat, P., et al. 2016, A&A, 594, A39
Froning, C. S., Kowalski, A., France, K., et al. 2019, ApJL, 871, L26
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Gershberg, R. E. 1989, MmSAI, 60, 263
Gershberg, R. E. 2005, Solar-Activity Type in Main-Sequence Stars (Berlin: Springer)
Gilliland, R. L., Jenkins, J. M., Borucki, W. J., et al. 2010, ApJL, 713, L160
Gizis, J. E., Paudel, R. R., Mullan, D., et al. 2017, ApJ, 845, 33
Gray, R. O., & Corbally, C. 2009, Stellar Spectral Classification by Richard O. Gray and Christopher J. Corbally (Princeton, NJ: Princeton Univ. Press)
Gray, R. O., & Corbally, C. J. 1994, AJ, 107, 742
Hawley, S. L., Davenport, J. R. A., Kowalski, A. F., et al. 2014, ApJ, 797, 121
Hilton, E. J., Hawley, S. L., Kowalski, A. F., et al. 2011, in ASP Conf. Ser. 448, 16th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. C. M. Johns-Krull, M. K. Brown, & A. A. West (San Francisco, CA: ASP), 197
Hodgson, R. 1859, MNRAS, 20, 15
Hunt-Walker, N. M., Hilton, E. J., Kowalski, A. F., et al. 2012, PASP, 124, 545
Iljin, E., Schmidt, S. J., Davenport, J. R. A., et al. 2019, A&A, 622, A133
Jenkins, J. M., Caldwell, D. A., Chandrasekaran, H., et al. 2010a, ApJL, 713, L120
Jenkins, J. M., Caldwell, D. A., Chandrasekaran, H., et al. 2010b, ApJL, 713, L87
Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJL, 713, L79
Lignières, F., Petit, P., Böhm, T., et al. 2009, A&A, 500, L41
Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2019, yCat, V/164
Mathur, S., Huber, D., Batalha, N. M., et al. 2017, ApJS, 229, 30
McQuillan, A., Mazeh, T., & Aigrain, S. 2014, ApJS, 211, 24
Mullan, D. J., & Mathioudakis, M. 2000, ApJ, 544, 475
Notsu, Y., Maehara, H., Honda, S., et al. 2019, ApJ, 876, 58
Osten, R. A., Godet, O., Drake, S., et al. 2010, ApJL, 721, 785
Parker, E. N. 1955, ApJ, 122, 293
Pedersen, M. G., Antoci, V., Korhonen, H., et al. 2017, MNRAS, 466, 3060
Pinsonneault, M. H., An, D., Molenda-Zakowicz, J., et al. 2012, ApJS, 199, 30
Reboll, L. M., Stauffer, J. R., Bouvier, J., et al. 2016, AJ, 152, 113
Reinhold, T., Reiners, A., & Basri, G. 2013, A&A, 560, A4
Rosner, R., & Vaiana, G. S. 1980, in Proc. of the NATO Advanced Study Institute, Vol. 60, X-Ray Astronomy, ed. R. Giacconi & G. Setti (Dordrecht: Reidel), 129
Schmitt, J. H. M. M., Guedel, M., & Predehl, P. 1994, A&A, 287, 843
Shibayama, T., Maehara, H., Notsu, S., et al. 2013, ApJS, 209, 5
Van Cleve, J. E., & Caldwell, D. A. 2016, Kepler Science Document, KSCI-19053-002
Van Cleve, J. E., Howell, S. B., Smith, J. C., et al. 2016, PASP, 128, 075002
Van Doorsselaere, T., Shariati, H., & Debosscher, J. 2017, ApJS, 232, 26
Švanda, M., & Karlický, M. 2016, ApJ, 831, 9
Wang, J.-J. 1993, IBVS, 3836, 1
Wang, S.-G., Su, D.-Q., Chu, Y.-Q., et al. 1996, ApOpt, 35, 5155
Wright, N. J., Drake, J. J., Mamajek, E. E., et al. 2011, ApJ, 743, 48
Xing, X., Zhao, C., Du, H., et al. 1998, Proc. SPIE, 3352, 839
Yang, H., & Liu, J. 2019, ApJS, 241, 29
Yang, H., Liu, J., Gao, Q., et al. 2017, ApJ, 849, 36
Zhao, G., & Li, H.-B. 2001, ChJAA, 1, 555
Zhao, G., Qiu, H. M., Chen, Y. Q., et al. 2000, ApJS, 126, 461
Zhao, G., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 723

Figure 12. The same as Figure 3, except for KIC 5360548.