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Analysis of Characteristics of Light Curve Profiles of the Flares Erupted from Sun-like Stars† ⋆

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Abstract Solar flares belong to a kind of eruptive phenomena caused by the sudden release of magnetic energy nearby sunspots. It is found that similar flares occurred as well in many Sun-like stars (called as Sun-like star flares). From the data acquired by the Kepler space telescope the SC (Short Cadence) data are mainly selected to make analysis, in order to find the characteristic parameters of light curve profiles of the flares erupted from Sun-like stars for a statistical study, and to summarize the activity features of these stellar flares. The analyzed results show that the light curve profiles and characteristic timescales of the flares of Sun-like stars are quite similar to those of solar flares, which may indicate the same physical mechanism for these two kinds of flares.

Key words stars: flares—stars: Sun-like—time—methods: statistical

1. INTRODUCTION

Solar flares are one of the most violent phenomenon of solar activities, the eruptions of solar flares are commonly accompanied by a series of energetic radiations. The frequency and intensity of flare activities are considered to be an important parameter for describing the strength of solar activities. Similar to solar flares, violent flare activities can also happen in the Sun-like stars. In this paper, we mainly study the features of light curve profiles of the Sun-like star flares observed by the Kepler space telescope[1]. The energy of a Sun-like star

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flare observed by the Kepler space telescope is $10^{33}\sim10^{37}$ erg[2], which belongs to the white light flare, and it is higher than the maximum energy of a solar flare (about 10^{32} erg)[3,4].

It is found by recent studies that there are some similarities between the physical mechanisms of Sun-like star flares and solar flares[5,6]. Candelaresi et al. studied the origin of super flares of E>10^{34}erg from the Kepler data of G, K, and M type stars, and obtained the results that the occurrence rate of super flares decreases with the increase of effective temperature, and the coverage rate of black spots is higher for the stars with a small rotation period[7]. In addition, Frasca et al. studied the magnetic activity and differential rotation of a typical young star, and found that its feature is also similar to the Sun[8]. Wichmann et al. found a fair amount of super flares in the Sun-like stars, and the common features of these stars are the young age and small rotation period[9]. Nogami et al. found that the rotation periods of some Sun-like stars producing super flares are similar to that of the Sun, in addition, they are more similar to one another in the aspects of effective temperature, surface gravity, and metal content[10].

However, the studies in above references were mainly based on the LC (Long Cadence) data selected from the Kepler data to perform a statistical analysis on super flares or the study on individual stars. The Kepler data are divided into the LC (Long Cadence) and SC (Short Cadence) data according to the time resolution[1]. The statistical analysis on the features of light curve profiles of stellar flares based on the SC data is a new study. The SC data will be selected from the data obtained by the Kepler space telescope for the analysis of this paper, in order to find the characteristic parameters of light curve profiles of Sun-like star flares by a statistical study, and to summarize the activity features of flares. In Section 2, we mainly introduce the origin and characteristics of data; and followed by Section 3, in which we describe the method of data analysis, analyze the features of light curve profiles of stellar flares, and obtain a preliminary result; finally, we make a physical analysis and discussion on the obtained result.

2. ORIGIN OF DATA

The advantage of Kepler space telescope for the observation of Sun-like star flares is the great amount of observed data of stars. The Kepler space telescope operated on the Earth-trailing heliocentric orbit was launched in 2009 for accurately detecting the Earth-like planets suitable for human life among the Sun-like stars by using the transit photometry method[1]. Only one photometer is carried by the Kepler, mainly for the measurement of stellar luminosity, to obtain the data of light curves of stars. The observed wavelength range is about 420$\sim$900 nm[1], which mainly belongs to the visible light band, thus only capable for observing the white light flares. The key component of the Kepler photometer is composed of 42 scientific CCDs. The single exposure time of CCDs is 6.2 s, and the time of readout is 0.52 s[1]. In the detecting process, the CCDs are continuously exposed to give rise to a great amount of data, which have to be integrated and overlapped before transmitting to the Earth for decreasing the data size, increasing the signal-to-noise ratio, and improving the quality of data, in favor of study. There are two methods to overlap the data obtained by the Kepler, one is to integrate and overlap the data of 270 exposures into one data point and transmit to the Earth, the time interval of integration and sampling of this kind data is about 30 min, which are called as LC data, and have important significance for recognizing flares; and another one is to integrate and overlap the data of 9 exposures into one data point and transmit to the Earth, and the time interval of integration and sampling of this kind of data is about 1 min, which are called as SC data, with a time resolution about 30 times higher than that of the LC data, they are important for analyzing the features of flare profiles. The sample number of SC data is relatively less due to the very large size of SC data. At an arbitrary time, while the LC data of 0.16 million stars may be obtained by the Kepler, only the SC data of 512 stars can be obtained. This paper mainly analyzes the features of light curve profiles of flares, so the study is performed based on the SC data. Furthermore, the Kepler data of every three months are ascribed to be one quarter. The Kepler telescope rotates 90° between two quarters, hence the star positions appeared in the Kepler's CCDs are different with the quarter. Moreover, as for the continuity of data, the monthly data within a quarter are continuous, but the data between two quarters may have some fluctuations because the different CCD modules are used.

3. DATA PROCESSING AND RESULT ANALYSIS

3.1 Analysis on the SC Data Obtained by the Kepler

At first, we select the data of Sun-like stars from the SC data of Kepler, draw the light curve of SC data and the light curve of corresponding LC data, respectively for the every star, then, we compare the two curves to recognize the positions of individual flares, and mark the corresponding flare positions on the overall light curve of SC data, then again to make a sample set after sorting. Fig.1 gives the light curve of a selected star with the ordinal number of KID4543412 (KID means the Kepler ID), and in which the positions of individual flares are marked, the abscissa represents the time (BJDC2454833, BJD means the Barycentric Julian Date, the deviation 2454833 means the Julian Date on 2009 January 1), and the ordinate refers to the relative flux $\Delta F/F_0$, here $\Delta F = F - F_0$ and F_0=mean(F), the short solid lines and the numbers above them mark respectively the positions and series numbers of the flares recognized, Fig(a) is the light curve drawn by the SC data, and Fig.(b) is the light curve drawn by the LC data.

Balona studied the SC data of stellar flares obtained by the Kepler, from which the morphologies and durations of flares can be measured accurately[11]. Hence, the amplified light curve profiles of the recognized individual flares can be drawn respectively, to make a sample set for a further statistical analysis on the features of flare profiles. Wang[12] has divided solar flares into 8 types according to the observations of solar flares in the optical, X-ray, and radio bands. We have classified the recognized sample of Sun-like star flares into 3 types according to the features of flare profiles: the flare profiles of the first type are relatively simple, which attain peak values in a short time after the flare eruption, and then decay rapidly; the flare profiles of the second type are somehow similar to the first type that they attain the maximum peak in a short time, but the difference is that the decay process of the second type is slower, and there may be two or more peaks during the eruptive process; and the difference of the third type of flares is that a longer time is needed to attain a peak value, and there may be multiple sub-peaks before decaying slowly, thus the total duration is much longer. Figs.2∼4 show respectively the examples of the three types of Sun-like star flares. The abscissa refers to the time, the upper and lower abscissa axes are respectively the BJD time and relative time (in units of hour) of the flare eruption; and the ordinate represents the relative flux. The three dashed lines vertical to the abscissa axis from left to right are successively the start time of flare's rising phase, the flare's peak time, and the ending time of flare's decay phase. The features of flare profiles can be obtained from these figures, such as the amplitude of flare eruption, the rising time, and decay time, etc., then the statistical analysis on these parameters can be performed.

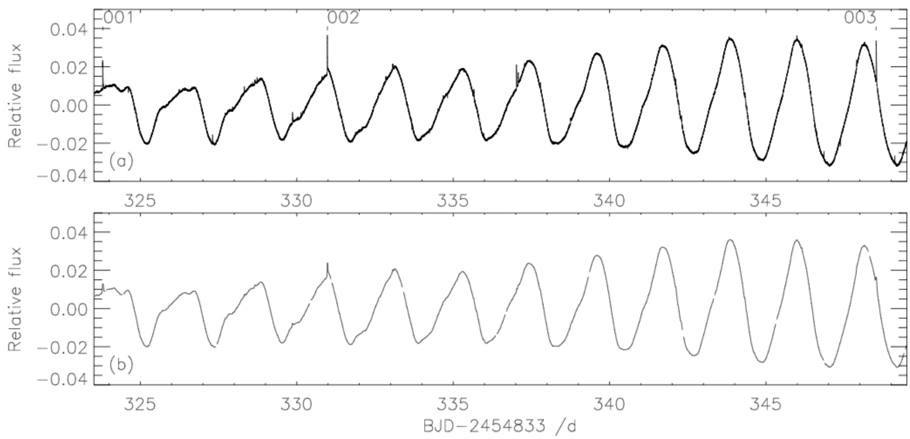

Fig. 1 The light curve of the Sun-like star KID4543412

3.2 Data Analysis and Discussion

From the SC data of Sun-like star flares detected by the Kepler, we have totally recognized 31 flare events. The various parameters of the selected flares are listed in Table 1, in which No. refers to the ID number of the flare, and the Kepler ID, quarter, and month are represented by KID, Q, and M, respectively. The observational time of the Kepler data in the first quarter is relatively short, with no difference of months, which is marked by "/" in Table 1; the flare class is represented by the character C, respectively of 1, 2, and 3 for the three types; $T1$ and $Y1$ respectively refer to the start time of flare eruption (BJDC2454833) and the relative flux. $T2$, $Y2$ and $T3$, $Y3$ are respectively the corresponding time (BJDC2454833) and relative flux at the maximum peak and the end of the flare; Dflux refers to the amplitude of flare eruption at the peak time, which is obtained by $Y2$-$Y1$; while $T2$-$T1$, $T3$-$T2$, and $T3$-$T1$ are the durations of the flare's rising and decay phases, and the flare's total duration (in units of hour), respectively.

After the amplified profiles of recognized flares are drawn individually, they are classified one by one, and the statistics for the flare amplitude, rising time, decay time, and total duration are performed to obtain the respective histograms.

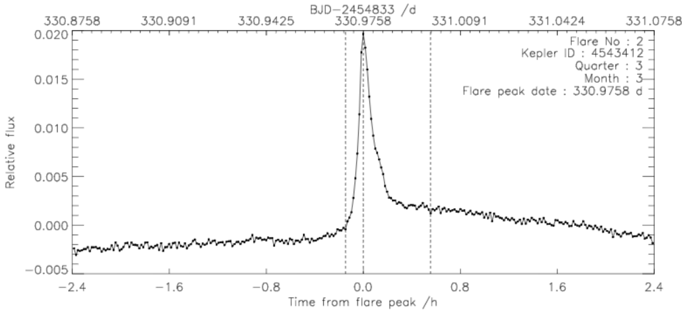

Fig. 2 Example of the first type of Sun-like star flare profile

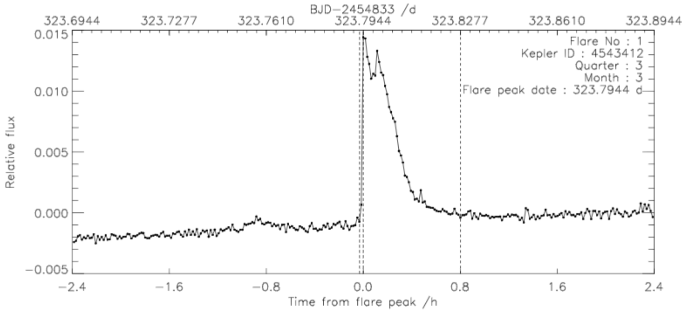

Fig. 3 Example of the second type of Sun-like star flare profile

Fig.5 gives the statistical histogram of eruption amplitudes of the Sun-like star flares, the abscissa represents the flare amplitude, and the ordinate refers to the number of flares in each amplitude interval. In this figure, the number of flares with an amplitude of $\leq$0.005 is zero, and there are a definite number of flares in the intervals started from the interval of 0.01, the number of flares is more in the intervals of 0.01$\sim$0.03, and the number of flares is decreased from the interval of 0.035. Viewing from the statistical number, the flares with an amplitude of 0.01$\sim$0.03 occupy 83.87% of total flares, the amplitudes of selected flares are concentrated in the intervals of 0.01$\sim$0.03. It is necessary to note that the criterion for the flare selection is the demand of an obvious light curve profile, while any candidate flares with an unclear or indeterminate profile are not adopted as sample flares.

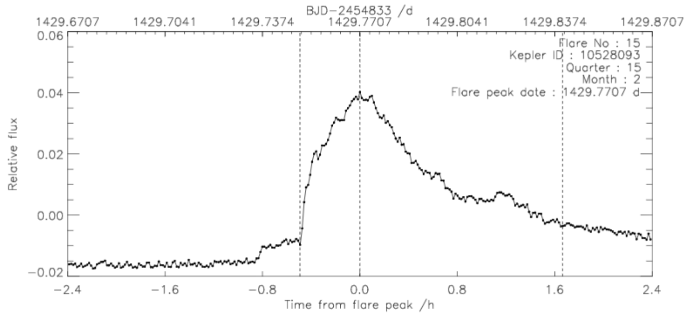

Fig. 4 Example of the third type of Sun-like star flare profile

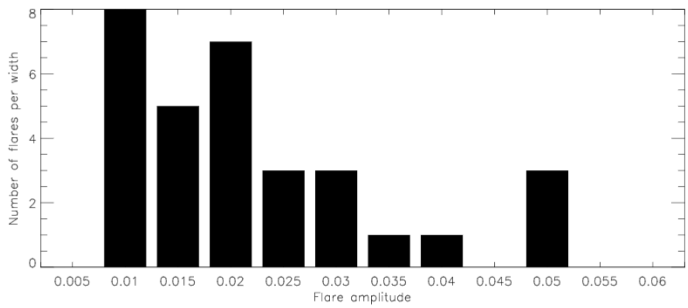

Fig. 5 Statistical histogram of flare amplitudes

Fig.6 gives the statistical histogram of flare's rising times, the abscissa represents the time, and the ordinate refers to the number of flares. In this figure, the number of flares in the interval of 0.09 h is the maximum, which occupies 35.48% of total flares, and the flares in the interval of 0.15 h occupy 16.13% of total flares, and the flare number is very small or zero in the every interval started from the interval of 0.21 h. From the statistical result, the rising times of flares are concentrated around 0.09 h, in addition, the flares with a rising time of <0.1 hour all belong to the first and second types of flares.

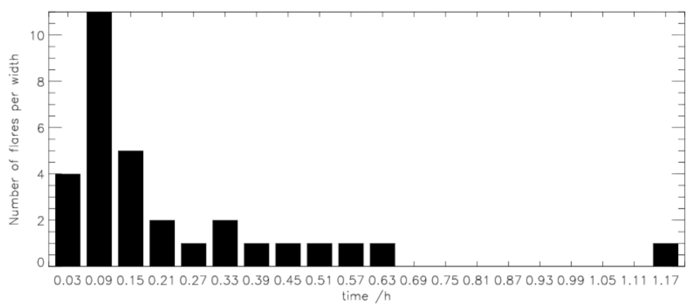

Fig. 6 Statistical histogram of the durations of flare rising phase

Table 1 Parameters of the sample flares selected from the SC data

No	KID	Q	M	C	$T1$ /d	$Y1$	$T2$ /d	$Y2$	$T3$ /d	$Y3$	Dflux	$T2$–$T1$ /h	$T3$–$T2$ /h	$T3$–$T1$ /h
1	4543412	3	3	2	323.7930	–0.0007	323.7944	0.0144	323.8277	–0.0004	0.0151	0.0336	0.7992	0.8328
2	4543412	3	3	1	330.9697	–0.0004	330.9758	0.0200	330.9989	0.0012	0.0204	0.1464	0.5544	0.7008
3	4543412	3	3	2	348.5202	0.0003	348.5229	0.0217	348.5454	–0.0020	0.0214	0.0648	0.5400	0.6048
4	4831454	4	1	2	354.0222	–0.0004	354.0250	0.0091	354.0590	–0.0004	0.0095	0.0672	0.8160	0.8832
5	4831454	14	3	2	1343.0141	–0.0003	1343.0161	0.0097	1343.0420	0.0001	0.0100	0.0480	0.6216	0.6696
6	6032920	14	1	1	1301.7373	0.0006	1301.7408	0.0112	1301.7544	–0.0003	0.0106	0.0840	0.3264	0.4104
7	6032920	14	2	2	1335.3718	–0.0016	1335.3752	0.0359	1335.4039	–0.0018	0.0375	0.0816	0.6888	0.7704
8	8226464	2	1	3	187.9888	–0.0070	188.0385	0.0150	188.1155	–0.0029	0.0220	1.1928	1.8480	3.0408
9	8226464	2	1	3	199.2649	–0.0026	199.2846	0.0091	199.3616	–0.0011	0.0117	0.4728	1.8480	2.3208
10	8226464	2	1	3	192.7976	–0.0019	192.8241	0.0073	192.8595	0.0002	0.0092	0.6360	0.8496	1.4856
11	9652680	2	3	3	235.4642	–0.0050	235.4887	0.0198	235.5466	0.0045	0.0248	0.5880	1.3896	1.9776
12	9652680	2	3	3	252.1119	–0.0057	252.1275	0.0276	252.1718	–0.0006	0.0333	0.3744	1.0632	1.4376
13	10528093	15	1	2	1381.5205	–0.0035	1381.5252	0.0106	1381.5974	–0.0027	0.0141	0.1128	1.7328	1.8456
14	10528093	15	2	2	1426.3516	–0.0011	1426.3584	0.0096	1426.4347	0.0009	0.0107	0.1632	1.8312	1.9944
15	10528093	15	2	3	1429.7503	–0.0101	1429.7707	0.0418	1429.8402	–0.0037	0.0519	0.4896	1.6680	2.1576
16	10646889	10	1	2	912.8089	–0.0018	912.8123	0.0200	912.8593	–0.0012	0.0218	0.0816	1.1280	1.2096
17	10646889	10	1	2	915.2521	–0.0025	915.2541	0.0463	915.2875	–0.0014	0.0488	0.0480	0.8016	0.8496
18	10646889	10	1	2	926.6004	–0.0034	926.6031	0.0484	926.6412	–0.0019	0.0518	0.0648	0.9144	0.9792
19	10646889	10	2	2	966.7482	–0.0021	966.7551	0.0088	966.8143	–0.0015	0.0109	0.1656	1.4208	1.5864
20	10646889	10	3	1	983.7780	–0.0006	983.7841	0.0089	983.8059	0.0006	0.0095	0.1464	0.5232	0.6696
21	10646889	10	3	1	994.1907	–0.0014	994.1928	0.0268	994.2071	0.0005	0.0282	0.0504	0.3432	0.3936
22	10646889	11	1	2	1002.9572	–0.0015	1002.9606	0.0199	1003.0021	–0.0013	0.0214	0.0816	0.9960	1.0776
23	10646889	11	3	2	1073.9358	–0.0025	1073.9453	0.0255	1073.9909	–0.0013	0.0280	0.2280	1.0944	1.3224
24	10745663	12	1	3	1112.8339	–0.0019	1112.8482	0.0176	1112.8945	–0.0001	0.0195	0.3432	1.1112	1.4544
25	10745663	12	2	3	1140.6585	–0.0031	1140.6715	0.0128	1140.7301	–0.0008	0.0159	0.3120	1.4064	1.7184
26	10745663	13	2	2	1224.8383	–0.0028	1224.8423	0.0143	1224.8839	0.0004	0.0171	0.0960	0.9984	1.0944
27	10745663	13	2	2	1240.9521	–0.0049	1240.9596	0.0236	1241.0216	–0.0021	0.0285	0.1800	1.4880	1.6680
28	10745663	13	3	2	1252.9696	–0.0025	1252.9730	0.0203	1253.0234	–0.0019	0.0228	0.0816	1.2096	1.2912
29	10745663	13	3	3	1269.5916	–0.0016	1269.5997	0.0199	1269.6379	0.0006	0.0215	0.1944	0.9168	1.1112
30	11610797	1	/	2	148.6287	–0.0032	148.6315	0.0214	148.7146	–0.0041	0.0246	0.0672	1.9944	2.0616
31	11610797	1	/	3	159.2859	–0.0023	159.2968	0.0113	159.3533	0.0012	0.0136	0.2616	1.3560	1.6176

Fig.7 gives the statistical histogram of flare's decay times, in which the flares in the intervals of 0.6∼1.4 h occupy 74.19% of total flares. Moreover, the number of flares in the interval of 1.0 h is the maximum.

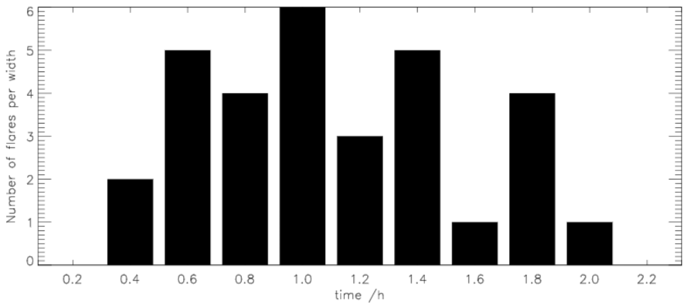

Fig. 7 Statistical histogram of the durations of flare decay phase

Fig.8 gives the statistical histogram of total durations of flares, in which the numbers of flares in the intervals of 0.8 h and 1.4 h are maximal. It is obtained by the statistics that the flares with the total durations of 0.6∼2.0 h occupy 83.87% of the total flares.

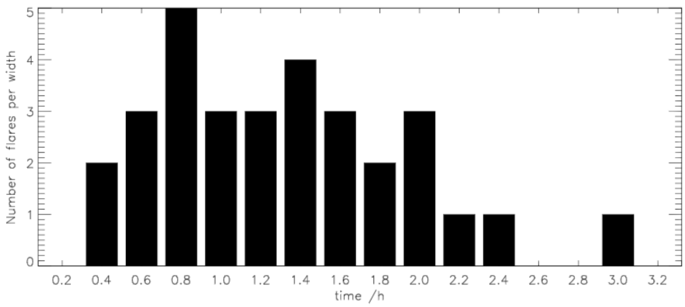

Fig. 8 Statistical histogram of the total durations of flares

In general, for the overall flare eruption process, the flare profile has an evident morphological variation of rising first and decaying later. In the duration of whole flare process, the rising phase occupies a smaller part, and the characteristic time is about 0.09 h, while the time of decay phase is relatively longer, and the characteristic time is about 1.0 h.

We can discuss and analyze physically the profiles and eruption times of Sun-like star flares as follows.

At first, for the flare profile itself, the shape of profiles is closely related to the magnetic configuration of the active region where the flare occurs. For the first type of flares, their profiles are relatively simple, they occupy about 12.9% of total flares, and therefore correspond to the simplest magnetic configurations. For the second type of Sun-like star flares, their flare profiles have a typical feature of fast rising and slow decay, they occupy about 54.8% of total flares, and belong to the type with frequent flares, and rather complicated magnetic configurations, there may be two or more sub-bursts appeared, in accompany with multiple magnetic energy release processes. For the third type of Sun-like star flares, which occupy 32.26% of total flares, there is a continuous energy release in the whole flare process.

Therefore, the variation of flare profile may indirectly reflect the magnetic configuration in the active region where the flare occurs.

Secondly, the characteristic times of the rising and decay phases of Sun-like star flares are quite similar to the time scales of solar flares, which implies that solar flares and Sun-like star flares may satisfy the same physical mechanism. There is a quasi-static process before and after the flare eruption, but it is a dynamic process from the start to the end of the flare eruption, which varies with time. The corona of a Sun-like star is similar to the solar corona, both belong to the state of plasma, thus both can be described by the same magnetohydrodynamic (MHD) equation[13,14]. The energy released by Sun-like star flares is higher than that of solar flares, but the characteristic times of two kinds of flares are similar to each other, hence, the spatial scale of the MHD equation should be increased to a certain value, however, the MHD equation is independent to the spatial scale. Therefore, no matter how much the spatial scale is increased, the characteristic time is the same.

Furthermore, the third type of Sun-like star flares can be compared with the solar compact flares, two-ribbon flares, and gradual flares[14]. Based on the knowledge of solar flares[15,16], we can make sense in four aspects: firstly, in morphology, the spatial scale increases gradually from the first type to the third type of flares; secondly, the energy release is always accompanied by the magnetic reconnection, the difference is that the magnetic reconnection is faster for the first and second types of flares, and the magnetic reconnection is slower for the third type of flares; thirdly, the three types of flares are all possibly accompanied by the energetic particle acceleration; finally, for the electromagnetic radiations of flares, a typical flare may cover multiple wavebands from radio, optical, EUV, to X-ray and γ -ray, and their intensities may vary with time differently. However, this is only the understanding based on the observation and study of solar flares, a further study is still needed for the detail similarities and differences between solar flares and Sun-like star flares. We may refer to the impulsive excitation mechanism of Sun-like stars and long-period variable stars proposed by Xiong et al.[17,18], and the study on the spectral classification of six comets made by Zhan et al.[19,20]. In addition, due to the relatively low energy of solar flares, it is difficult to recognize a white light flare from the solar light curve, the number of white light flares recognized from the solar light curves is less. Meanwhile, the typical event of solar white light flare in Fig.2 of Thomas et al.[21] is very similar to the second type of flares of this paper.

4. SUMMARY

Based on the statistical study on the light curve profiles of flare events in the SC data of the Kepler telescope, we can conclude that the eruption of Sun-like star flares is a dynamic process, and it is quite complicated. In addition, different flares may have different morphologies and evolutionary processes. For solar flares, the flare's evolution basically includes three phases: the first is the precursor, its typical timescale varies from several minutes to several ten minutes; the second the impulsive phase, with a timescale from several minutes to several ten minutes, while the flare profile exhibits the rising and decay variations; and the third is the decay phase, with a time scale from several ten minutes to one or two hours[14,15]. The characteristic time of the rising phase for the Sun-like star flares is 0.09 h, 1.0 h is the decay phase, and 1.1 h is the total duration of flare eruption. Therefore, the rising phase, maximum phase, and decay phase as well as the eruption duration of Sun-like star flares are all similar to the eruptive process of solar flares. Hence, in both the characteristic time and profile variation, the Sun-like star flares are very similar to solar flares, and all can be described by the same MHD equation. We can believe that the Sun-like star flares have the same physical mechanism as that of solar flares.

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