Detection of Optical Flares on the Selected G-M Dwarfs from Long-term Photometric Series

N. I. Bondar\textsuperscript{1,*}, M. M. Katsova\textsuperscript{2,**}, and A. A. Shlyapnikov\textsuperscript{1,***}

\section*{Abstract}
We have carried out a search for flares from the analysis of light curves for 12 active G, K, and M dwarfs. As sources of data we used ground-based observations in 2000–2020 from the photometric databases ASAS, SuperWASP, KWS. Events of low-amplitude brightening ($\Delta V < 0.25$ mag), which possibly could be flares, were revealed for 11 stars. A large number of such increases in brightness were found on K dwarfs. Events of increasing in $V$-magnitudes to 0.5 mag or more were detected on light curves of one G star, BE Cet, and two M dwarfs. For three flares we could follow their development with time. We have estimated the duration of these flares; they lasted more than an hour, but less than 3 hours. In most cases we could not determine a lifetime of the suggested flares, but we believe that most of the probable flares on the investigated cool dwarfs are short-lived, on the order of several minutes.

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\textbf{Keywords}
stars: low-mass stars -- stars: activity -- stars: flares -- techniques: long-term photometry

1 Crimean Astrophysical Observatory, Russian Academy of Sciences, Nauchny, Russia
2 Sternberg State Astronomical Institute, Lomonosov Moscow State University, Moscow, Russia
* e-mail: otbn@mail.ru
** e-mail: maria@sai.msu.ru
*** e-mail: aas@craocrimea.ru

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\section*{1. INTRODUCTION}
Starspots and flares in the atmospheres of low-mass G-M stars are proxies of their magnetic activity manifestation. Since the 1960s, these structures have been studied in different spectral ranges using ground-based and space observations. Starspots are a cause of low-amplitude variations in brightness with the rotation period of a star and the long-term variability, often cyclical changes, by a few or even tens of percent relative to the quiescent state of a star.

Although flares are associated with starspots, they are irregular phenomena that produce significant rapid increases of radiation in the optical continuum, emission lines, and in X-ray fluxes. On the UV Cet type stars (flaring M dwarfs), most of the detected flares are classical, i.e. with a fast rise in brightness up to several magnitudes and a subsequent gradual decay. The energies of such flares reach $10^{30} - 10^{34}$ erg. A review of studies concerning flare activity on the main-sequence G-M stars is given in the recently published monograph by Gershberg et al. (2021). The efforts of astronomers are currently aimed at studying flares in the visible range of wavelengths and at searching for powerful stellar flares.

The white-light flares were discovered on the Sun observing the intensity of radiation from the Sun as a star. The contribution of optical flares can be traced over all spectral regions; their energy distribution corresponds to blackbody radiation with a temperature of 9000 K (Kretzschmar, 2011). Due to observations from the \textit{Kepler} mission, the manifestations of activity have been studied for a large number of solar-type and cool stars (for instance, Davenport, 2016; Savanov and Dmitrienko, 2017; Namekata et al., 2019). As shown by the results of the recent statistical analysis of flares on G dwarfs based on data of the \textit{Kepler} mission and Gaia-DR2 catalog, non-steady events on solar-like stars can reach energies within $10^{36}$ erg (Okamoto et al., 2021). On the modern Sun there occurred flares with total energies not exceeding $3 \times 10^{32}$ erg, and only the Carrington flare on September 1, 1859 is estimated of several times powerful. By studying optical radiation from stars in a certain range of physical parameters, it is possible to determine both typical and maximum flare energies, to trace their development on G-M dwarfs with different ages, and to investigate the distribution of flare energies. This knowledge is necessary for studying the formation of planetary systems and their environment. The study of solar-like stars is important to understanding whether superflares were produced over the lifetime of the Sun. Here we present the results of a search for flares on 12 G-M dwarfs derived from the long-term ground-based photometry. Our sample includes both poorly studied stars and well-known ones with high-level flare activity. The brightness of the most
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Table 1. Sample of investigated G-M dwarfs and number of positive $\Delta V$ (events of possible flares)

| Star                | Spectral type | $V$, mag | Number of $\Delta V < 0.25^{\text{mag}}$ | $\Delta V > 0.3^{\text{mag}}$ |
|---------------------|---------------|----------|------------------------------------------|-------------------------------|
| HD 1835, BE Cet     | G3 V          | 6.39     | 2 (K)                                    | 0.3(K), 0.5 (K)              |
| HD 4747, GJ 36      | G9 V          | 7.16     | 4 (A)                                    | –                             |
| HD 97334, MN UMa    | G1 V          | 6.41     | –                                        | –                             |
| HD 168443, NSV 24398| G6 V          | 6.92     | 2(A), 2(K)                               | –                             |
| HD 17382, BC Ari    | K1 V          | 7.62     | 4 (K)                                    | –                             |
| HD 61606, V869 Mon  | K2 V          | 7.17     | 8(A), 10(K)                              | –                             |
| HD 283750, V833 Tau | K2 V          | 7.90     | 5(A), 4(S), 9(K)                         | –                             |
| HD 45088, OU Gem    | K3 V          | 6.75     | 1(A), 5(K)                               | –                             |
| HD 197481, AU Mic   | M1 V          | 8.63     | 7(K)                                     | 0.32(K)                      |
| EV Lac, GJ 873      | M4 V          | 10.26    | 1(K)                                     | 1.08 (K)                     |
| GJ 1243, KIC 972699 | M4 V          | 12.7 ($m_{KP}$) | 9(S)                                      | –                             |
| YZ CMi, GJ 285     | M4.5 V        | 11.22    | 3(A), 7(K)                               | 0.5(A), 0.67(K)              |

Letters A, K, S in brackets indicate catalogs ASAS, KWS, SW; the magnitude $m_{KP}$ of the star GJ 1243 is given according to the Kepler mission data.

selected objects was studied during the 20-year time interval, but in most cases the data in catalogs of ground-based observational programs have been obtained with a low-time resolution and a short-time continuous monitoring during a night. Therefore, our work aims to reveal events of increase in brightness, which may indicate the development of flares, to determine the maximum $V$-values for possible flares and also their number for dwarfs of different spectral types. Section 2 contains a list of objects in our research and a description of the used databases, Sections 3 and 4 contain processing methods and results, a brief discussion of results is given in Conclusions.

2. OBJECTS FOR THE RESEARCH AND DATA SOURCES

Flares on stars located on the lower part of the main sequence are an irregular, stochastic phenomenon, and their detection requires a systematic many hour monitoring of stellar brightness during a night. The long-term observational data for a large number of stars are contained in a convenient form in photometric databases All-Sky Automated Survey (ASAS) (Pojmanski, 1997, 2002), the SuperWASP photometric survey (SW) (Pollacco et al., 2006; Norton et al., 2007; Butters et al., 2010), the Kamogata Wide-field Survey (KWS) (Maehara, 2014).

These databases are effective sources of data for studying starspots on the surface of G-M dwarfs, for determining rotation periods of stars and parameters of rotational brightness modulation, and also for searching for cycles of photospheric activity. The light curves constructed from these data often show short-term increases in brightness, which are usually considered as outliers and are excluded from data series which are analyzed for systematic variability. Some of these brightness increases are likely caused by real flares.

Based on the available nearly 20-year data, we can explore whether a significant increase in brightness of the star may be considered as flares observed over this span. The ASAS archive can be used to study the brightness behavior from 2000 to 2009. The best photometric accuracy was derived for stars with magnitudes in the range of $8 < V < 12$ mag. The SuperWASP photometric catalog contains the results of observations obtained in 2004–2008 for the stars brighter than 15 mag. The accuracy of data for stars with a magnitude of $8 < V < 11.5$ reaches 1%, the errors increase for brighter and fainter stars (Pollacco et al., 2006; Norton et al., 2007).

The survey observations of Kamogata Wide-field Survey (KWS) started in 2010 and are currently being continued in bands $B, V, I$. Data series in the $V$-filter are more numerous. The errors of observations are given for each $V$-value, photometric precision is not less than 5% for stars with magnitudes of $5 < V < 11.5$ (Maehara, 2014).

We selected 12 G-M dwarfs, out of 4 stars in each spectral group (Table 1), taking into account indices of activity of stars, their stellar magnitudes, the time span of data series in the $V$-filter in the indicated catalogs. As we noted above, in the used catalogs errors of observations of $V$-values increase for both faint and bright stars, therefore we have included in our sample stars with magnitudes in the range of $6.4 < V < 13$ mag, G dwarfs are the brightest among them.

Two G stars, BE Cet and MN UMa, are young solar analogs (Radick et al., 2018). The sample of K dwarfs includes active BY Dra-type stars – V833 Tau and OU Gem. The group of M dwarfs includes the stars AU Mic, EV Lac, YZ CMi, which are known by their high-level flare activity, also the star GJ 1243, for which a large number of flares have been found from the extra-atmospheric observations (Hawley et al., 2014; Silverberg et al., 2016).

3. SEARCH FOR POSSIBLE FLARES

For each star under study, the preliminary processing of data series was performed. As a result, we obtained a series of $V$-magnitudes sorted by Julian dates, from which the random
Figure 1. Examples of the selected observational series from different catalogs and possible flares for V869 Mon (KWS), V833 Tau (SW), open circles mark data for a comparison star, and YZ CMi (ASAS).

significantly fainter $V$-values were excluded. Records in the ASAS catalog contain for each of the five observation cameras the observation times (Julian dates), $V$-magnitudes, and their errors. We have compared records from different cameras, and for further calculations there were chosen 2–3 cameras with smaller observational errors and the best coincidence of light curves.

Then we determined average magnitudes at the moments of observations and corresponding errors. The full data series obtained by this way contain up to 700 $V$-values, but in the observational date 1–2 measurements were taken usually, sometimes up to 4. Data series in the KWS catalog include several hundreds of measurements covering the seasonal intervals of observations well, for a date of observation there are given 2–4 estimates of brightness, for some dates two exposures were made at the beginning and at the end of the 40-min cadence.

The SW catalog contains a large number of data, up to several thousand, obtained by several cameras with a time resolution of 6–8 min. The time of monitoring was several hours over a night. We examined the data series from the SW archive and selected the sets with the largest number of records from one of the cameras for a more detailed analysis. Using the SW catalog we could study only two stars, V833 Tau and GJ 1243, a research of other chosen stars was performed based on data of the ASAS and KWS catalogs.

We constructed light curves from data of each catalog and found for each continuous set of observations the mean magnitudes $V_{av}$, standard deviation $\sigma$, and for the further flare search process we selected sets with positive $\Delta V = V_i - V_{av} > 2.5\sigma$. A similar simple statistical analysis was made in studies of data series from the Kepler mission and the ASAS-SN catalog (Hawley et al., 2014; Martinez et al., 2020). In most cases, increases in brightness confirmed by two or more consecutive records of observations were considered as possible flares. We have found clear evidence for reality of the suspected flares for some stars, comparing their light curves with ones for comparison stars observed simultaneously. In addition, for the stars with the known rotation periods, phase curves were also constructed. This allows us to take into account variations in the light curve produced by rotational modulation due starspots, and also to determine phases of an appearance of possible flares.

4. RESULTS ON IDENTIFICATION OF FLARE EVENTS

The events of low-amplitude ($\Delta V < 0.3$ mag) and short-term increases in brightness relative to the average value in the selected interval were found for all the stars of our sample, except for MN UMa (G1 V). The number of such events is given in Table 1. An increase in brightness up to 0.3–0.5 mag was detected for the stars BE Cet (G3 V) and AU Mic (M1 V), possible flares of 0.5–0.67 mag were found in light curves of the star YZ CMi (M4.5 V). Analysis of the KWS data for the star EV Lac (M4 V) allowed us to define one event of an
increase in its brightness by 0.18 mag (4σ) and one significant brightening up to 1.08 mag detected from 4 measurements at the beginning of observations on July 14, 2011. If this flare is real, its duration is not less than 30 min. Figure 1 shows examples of the light curves from different catalogs for some stars. For stars with the known rotation periods, we have constructed phase light curves to resolve an issue whether the moments of appearance of possible flares and development of starspots are consistent. Flares on the stars BE Cet and V833 Tau have been observed at phases that are distant from the minimum produced by the maximum contribution of cool starspots.

Using the SW catalog, a search for flares was performed for two stars: for GJ 1243 (M4 V) we studied light curves from observations on June 4, 2007 and July 10, 2007 (Fig. 2), for V833 Tau (K2 V) we analyzed data on December 14, 2006 (Fig. 3).

The presence of increases in brightness is confirmed by the light curves of comparison stars. Figures 2 and 3 (right panels) show changes in the $V$-values over time in minutes from the moment of maximum of increases relative to the average value for the considered interval. The relative intensity $f_r = f_i/f_c - 1$, where $f_i$ was calculated by the formula $-0.4m = \log f_i$, $f_c$ is the average value, $m = V_i$. The increase in brightness for both stars is no more than 15%. In order to determine the onset and the end of a possible flare, the $f_r$-values were smoothed by moving averages over 5 points. According to our estimates, flares on GJ 1243 have duration of 1.4 h and 2.4 h, and duration of the flare on V833 Tau was 2.2 hours.

The considered photometric catalogs contain results of sur-
vey observations, i.e. short-term brightness estimates, which allow one to register only those rare flares that occur at the moment of observation. Nevertheless, such random registrations characterize to a certain extent the flare activity of the star. For each catalog and each star, we determined the frequency of brightness increases (possible flares) on the value of $\Delta V < 0.25$ mag. Its average value for each spectral type can be considered as a characteristic of the flare activity of stars of this spectral type.

The frequency of flares is $n = N_f / T_{obs}$, where $N_f$ is the number of the registered flares in the observation interval, $T_{obs}$ is the observation time of the star, $T_{obs} = t_{exp}N$, here $t_{exp}$ is the exposure time, $N$ is the number of $V$-data. Table 2 lists the values of $n$ for stars studied from the KWS catalog data series. For G stars, the average value $n$ is 0.26, for K and M dwarfs – 0.36 and 1.06, respectively.

5. CONCLUSIONS

We have undertaken a search for flares on 12 active G-M dwarfs, studying about 150 light curves constructed from long-term photometric series of the ASAS, SuperWASP, and KWS catalogs. Short-term increases in brightness, which do not exceed 0.3 mag, were detected for 11 stars, on three stars there were revealed several possible flares with an increase in brightness of 0.3 – 0.6 mag, one flare up to 1 mag was suspected for EV Lac.

The detected events of possible flares are few for the considered 20-year spans and give poor statistics, nonetheless the obtained results confirm the well known conclusion that the number of flares increases for cool stars, and their amplitude increases also. On K dwarfs we observed mainly low-amplitude flares. Among several dozen events on these dwarfs, there was no any potential flare with high amplitude.

The result on the flare activity of BE Cet, a young solar analog on which, in addition to low-amplitude ones, flares up to 0.5 mag are possible, deserves further consideration. For each star, we have studied some series of observations, and we can note that stars have epochs of weak and strong flare activity. Long-term data from photometric surveys can be useful to study changes in the level of flare activity.

Single estimates of brightness on the date of observations stored in the ASAS and KWS catalogs do not allow us to determine the duration of the suspected flares, but most of them are likely short-lived and lasting for a few minutes. Using the SW database, we traced the development of two flares on the star GJ 1243 and one flare on V833 Tau. According to our estimates, their duration was within 1.4–2.4 hours.

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8. CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.
Table 2. Estimates of the number of flares with $\Delta V < 0.25$ from the KWS data series

| Star       | Spectral type | Time interval JD245000+ | Number of data | $T_{\text{obs}}$ of star, h | Number of flares | Number of flare/h |
|------------|---------------|-------------------------|----------------|-----------------------------|------------------|-------------------|
| HD 1835    | G3 V          | 5548–8841               | 703            | 6.75                        | 2                | 0.30              |
| HD 168443  | G6 V          | 5661–9067               | 615            | 8.86                        | 2                | 0.22              |
| HD 17382   | K1 V          | 5527–8866               | 979            | 14.10                       | 4                | 0.28              |
| HD 61606   | K2 V          | 5891–8937               | 1285           | 18.50                       | 10               | 0.54              |
| HD 45088   | K3 V          | 5516–8550               | 1214           | 14.57                       | 5                | 0.34              |
| HD 197481  | M1 V          | 6457–8420               | 464            | 3.30                        | 7                | 2.09              |
| EV Lac     | M4 V          | 5757–8451               | 638            | 9.19                        | 1                | 0.11              |
| YZ CMi     | M4.5 V        | 6235–8573               | 608            | 5.73                        | 7                | 0.87              |

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