A NEW METHOD FOR CLASSIFYING FLARES OF UV Ceti TYPE STARS: DIFFERENCES BETWEEN SLOW AND FAST FLARES

H. A. Dal and S. Evren
Department of Astronomy and Space Sciences, University of Ege, Bornova, 35100 Izmir, Turkey; ali.dal@ege.edu.tr
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1. INTRODUCTION

Flares and flare processes are heavily studied subjects of astrophysics. A large number of studies on flares have been carried out since the first flare was detected on the Sun by R. C. Carrington and R. Hodgson on 1859 September 1. Flare processes have not been perfectly understood yet (Benz & Güdel 2010). However, the research indicates that the incidence of red dwarfs in our Galaxy is 65%. Seventy-five percent of them are almost equal to their decay times.

As a result, flares can be separated into two types, slow and fast, depending on the ratio of flare decay time to flare rise time. The ratio is below 3.5 for all slow flares, while it is above 3.5 for all fast flares. Also, according to the independent samples t-test, there is a difference of about 157 s between equivalent durations of slow and fast flares. In addition, there are significant differences between amplitudes and rise times of slow and fast flares.

Key words: methods: data analysis – methods: statistical – stars: flare – stars: individual (AD Leo, EV Lac, EQ Peg, V1054 Oph)

Online-only material: machine-readable and VO tables, supplementary data

In this study, a new method is presented to classify flares derived from the photoelectric photometry of UV Ceti type stars. This method is based on statistical analyses using an independent samples t-test. The data used in analyses were obtained from four flare stars observed between 2004 and 2007. The total number of flares obtained in the observations of AD Leo, EV Lac, EQ Peg, and V1054 Oph is 321 in the standard Johnson U band.

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Two types of flares. However, Oskinian (1969) divided flares into four classes. Like Oskinian (1969), considering only light variation shapes of the flares, Moffett (1974) directly classified flares such as classical, complex, slow, and flare event types. On the other hand, Kunkel had asserted another idea in his PhD thesis in 1967 (Gershberg 2005, p. 53). According to Kunkel, the observed flare light variations must be due to a combination of slow and fast flares. According to this idea, there are only two main flare types. The complex flares mentioned by Moffett (1974) are actually a combination of fast and slow flares. Also, both the slow flares and flare events mentioned by Moffett (1974) can be classified as the same type of flares.

Gurzadian (1988) described two types of flares to model flare light curves. Gurzadian (1988) indicated that thermal processes are dominant in the processes of slow flares, which are 95% of all flares observed in UV Ceti type stars. Non-thermal processes are dominant in the processes of fast flares, which are classified as “other” flares. According to Gurzadian (1988), there is a large energy difference between these two types of flares.

In this study, we introduce a new statistical method for classifying flares. This method is based on the distribution of flare equivalent durations versus flare rise times using a statistical independent samples t-test analysis (hereafter t-test). Considering the studies in Osawa et al. (1968), Kunkel’s PhD thesis (Gershberg 2005, p. 53), and Gurzadian (1988), we assume that there are two types of flares, namely fast flares and slow flares. We classify flares into two types and demonstrate the similarities and differences between these two types of flares. In respect of these analyses, we discuss the results obtained from analyses of 321 flares detected in U-band observations of the flare stars AD Leo, EV Lac, EQ Peg, and V1054 Oph between 2004 and 2007. The program stars were selected for this study due to their high flare frequencies (Moffett 1974). The flare data obtained in this study are useful for such an analysis. This is because the data were obtained with systematical observations and using the same method.

The flare activity of AD Leo was discovered for the first time by Gordon & Kron (1949). The star is a red dwarf and a member of The Castor Moving Group, whose age is about 200 million...
years (Montes et al. 2001). Crespo-Chac et al. (2006) found that the flare frequency of AD Leo was 0.71 h⁻¹. The variation of the flare frequency was investigated by Ishida et al. (1991). They mentioned that there is no variation in the flare frequency of AD Leo. The other star in this study is EV Lac, which is one of the well-known UV Ceti stars. According to the spatial velocities, EV Lac seems to be a member of the 300 million year old Ursa Major Group (Montes et al. 2001). It has been known since 1950 that EV Lac shows flares (Lippincott 1952; Van de Kamp 1953). The largest observed flare amplitude is 6.4 mag in U-band observations of EV Lac. Andrews (1982) detected 50 flares in U- and B-band observations of EV Lac. The author indicated that about 42 out of 50 flares were found in some groups, which occurred every five to six days. When seasonal flare frequencies were computed from 1972 to 1981, these frequencies were compared with the seasonal averages of B-band magnitudes. According to this comparison, it was found that the activity cycle is about five years for EV Lac (Mavridis & Avgoloupis 1986). On the other hand, Ishida et al. (1991) indicated that there was no flare frequency variation from 1971 to 1988. In another study, Leto et al. (1997) showed that flare frequencies of EV Lac increased from 1968 to 1977. EQ Peg is another active flare star, whose flare activity was discovered by Roques (1954). EQ Peg is classified as a metal-rich star and it is a member of the young disk population in the galaxy (Veeder 1974; Fleming et al. 1995). EQ Peg is a visual binary (Wilson 1954). Both components are flare stars (Pettersen et al. 1983). The angular distance between the components is between 3°5 and 5°2 (Haisch et al. 1987; Robrade et al. 2004). One of the components is 10.4 mag and the other is 12.6 mag in the V band (Kukarin 1969). Observations show that flares of EQ Peg generally come from the fainter component (Fossi et al. 1995). Rodonó (1978) proved that 65% of the flares come from the faint component and about 35% from the brighter component. The fourth star in this study is V1054 Oph, whose flare activity was discovered by Eggen (1965). V1054 Oph (= Wolf 630AAB, Gliese 644ABab) is a member of the Wolf star group (Joy 1947; Joy & Abt 1974). Wolf 630ABab, Wolf 629AB (= Gliese 643AB), and VB8 (= Gliese 644C) are the members of the main triplet system, whose scheme is demonstrated in Figure 1 given in the paper of Pettersen et al. (1984). Wolf 630 and Wolf 629 are a visual binary and they are separated by 72" from each other. Wolf 630AB is a close visual binary in itself. Wolf 629AB is a spectroscopic binary. The B component of Wolf 629AB seems to be a spectroscopic binary. VB8 is 220" from the other components. There is an angular distance of about 0°218 between the A and B components of Wolf 630 (Joy 1947; Joy & Abt 1974). The masses were derived for each component of Wolf 630AAB by Mazeh et al. (2001). The author showed that the masses are 0.41 M⊙ for Wolf 629A, 0.336 M⊙ for Wolf 630Ba, and 0.304 M⊙ for Wolf 630Bb. In addition, Mazeh et al. (2001) demonstrated that the age of the system is about 5 Gyr.

2. OBSERVATIONS AND ANALYSES

2.1. Observations

The observations were acquired with a High-speed Three Channel Photometer attached to a 48 cm Cassegrain-type telescope in the Ege University Observatory. Using a tracking star set in a second channel of the photometer, the observations were continued in the standard Johnson U band with an exposure time between 2 and 10 s. The basic parameters of all program stars and their comparisons are given in Table 1. The parameters given in the table are star name, magnitude in the V band, B − V color index, spectral type, distance (pc), and bolometric luminosity (log Lbol, erg s⁻¹). The magnitudes and color indices were obtained in this study. Considering B − V color indices, the spectral types were taken from Tokunaga (2000). The distances and bolometric luminosities were taken from Fossi et al. (1995) and Gershberg et al. (1999).

Although the program and comparison stars are very close to one another on the sky, differential extinction corrections were applied. The extinction coefficients were obtained from observations of the comparison stars on each night. Moreover, the comparison stars were observed with the standard stars in their vicinity and the reduced differential magnitudes, in the sense of variable minus comparison stars, were transformed to the standard system using the procedures outlined in Hardie (1962). The standard stars are listed in the catalogs of Landolt (1983, 1992). Heliocentric corrections were applied to the times of the observations. The standard deviation of observation points acquired in the standard Johnson U band is about 0°015 on each night. Observational reports of all program stars are given in Table 2. It is seen that there is no variation of differential magnitudes in the sense of comparison minus check stars.

Gershberg (1972) developed a method for calculating flare energies. Flare equivalent durations and energies were
calculated using Equations (1) and (2) of this method,

\[ P = \int [(I_{\text{flare}} - I_0)/I_0] dt. \]  

(1)

In Equation (1), \( I_0 \) is the intensity of the star in the quiescent level and \( I_{\text{flare}} \) is the intensity during flare.

\[ E = P \times L, \]  

(2)

where \( E \) is the flare energy, \( P \) is the flare equivalent duration, and \( L \) is the luminosity of the stars in the quiescent level in the Johnson \( U \) band.

HJD of flare maximum times, flare rise and decay times, amplitudes of flares, and flare equivalent durations were calculated for each flare. The brightness of a star without a flare was taken as a quiescent level of the brightness of this star on each night. Considering this level, all flare parameters were calculated for each night. It was seen that some flares have a few peaks. In these cases, the flare maximum times and amplitudes were calculated from the first highest peak. Instead of flare energies, flare equivalent durations were used for all statistical analyses. This is because of the luminosity term in Equation (2). The luminosities of stars from different spectral types have large differences. Although the equivalent durations of two flares obtained from two stars in different spectral types are the same, calculated energies of these flares are different due to different luminosities of these spectral types. Therefore, we could not use these flare energies in the same analyses. On the other hand, flare equivalent duration depends only on flare power. Another reason for using equivalent duration is that the given distances of the same star in different studies are quite different. The calculated luminosities became different because of these different distances.

All the calculated parameters of flares are given in Table 3. The parameters given in the columns are star name, observation date, HJD of flare maximum, flare total time (s), decay time (s), equivalent duration (s), energy (erg), amplitude (mag), and flare type are given, respectively. In the last column, it is specified whether the flare was used in the analyses or not. (This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

When the observed flares are examined, it is seen that almost each flare has a distinctive light variation shape (Figures 1–4). These figures, the horizontal dashed lines represent the level of quiescent brightness. The flare shown in Figure 1 is a fast flare. This flare type occurs frequently in UV Ceti type stars. On the other hand, the first flare shown in Figure 2 is a compact flare. This flare type among the others is the hardest flare type to classify. This flare type must be a combination of two flares. The observed flares, whose light variations are similar to the first flare in Figure 2, were not used in the analyses. The second flare shown in Figure 2 is a fast flare. The flare shown in Figure 3 is a powerful flare, but its light variation was not fully completed because we did not perform observations until the flare completely decreased to the quiescent phase due to the Sun rising. If the light variation observation of a flare was not completed like this one, the flare was not used in the analyses. The flare shown in Figure 4 seems to be very different from previous flares. Moffett (1974) called flares like this one flare...
events. They are called slow flares in some other studies. In this study, we use the term slow flares.

2.2. Analyses

The impulsive phase of a flare is the time interval where sudden high energy occurs. On the other hand, the mean phase is the other part of the flare, where the energy is emitted to all space (Gurzadian 1988; Benz & Güdel 2010). Moreover, the rate of brightness increase for fast flares is clearly higher than that of slow flares (Gurzadian 1988; Gershberg 2005, p. 53). Moreover, Gurzadian (1988) stated that the energies of fast flares are always higher than slow flare energies.

According to this approach, we examined all flare data and we saw that the equivalent durations of some flares are different, while their rise times are the same. For example, the rise time of 22 flares is 15 s. The equivalent durations of eight flares among them are very high, while the equivalent durations of the other 14 flares are dramatically low. It was seen in 30 different rise times. It means that there are at least two flares in 30 different rise times and their equivalent durations are different from each other. In total 140 flares were chosen. These 140 flares used in the analyses are specified in the last column of Table 3.

It was tested whether these linear functions belong to two independent distributions or not. At this point, the slopes of linear functions were principally examined. As can be seen in Table 4, the slope of the linear function is $1.109 \pm 0.127$ for slow flares, while it is $1.227 \pm 0.243$ for fast flares. This shows that the increase in equivalent durations versus flare rise times for both fast and slow flares is parallel. When the probability, $p$
Table 4

| Flare Groups | Slow Flare | Fast Flare |
|--------------|------------|------------|
| Data Total number of Flares | 30 | 30 |

Best representation values

| Slope when $x = 0.0$ | $1.109 \pm 0.127$ | $1.227 \pm 0.243$ |
| $y$ intercept when $x = 0.0$ | $-0.581 \pm 0.226$ | $0.122 \pm 0.433$ |

Mean average of all $Y$ values

| Mean average | 1.348 | 2.255 |
| Mean average error | 0.092 | 0.126 |

Goodness of fit

$\rho^2$ | 0.732 | 0.476 |

Is slope significantly non-zero?

$p$-value | <0.0001 | <0.0001 |

Deviation from zero? Significant Significant

Notes. The results obtained from both the regression calculations and the $t$-test analyses performed to the mean averages of the equivalent durations (log($P_u$)) versus flare rise times (log($T_r$)) in the logarithmic scale are listed.

value, was calculated to say whether it is statistically significant, it was found that $p = 0.670$. This value indicates that there is no significant difference between the slopes of fits.

Finally, the $y$-intercept values were calculated and compared for two linear fits. While this value is $-0.581$ for the slow flares, it is $0.122$ for the fast flares in the logarithmic scale. It means that there is a difference of about 0.703 between these values in the logarithmic scale. When the probability value was calculated for the $y$-intercept values to say whether there is a statistically significant difference, it was found that $p < 0.0001$. This result indicates that the difference between two $y$-intercept values is clearly important.

Some other differences like those demonstrated by the $t$-test can be directly seen in the figures. For example, the lengths of flare rise times for both types of flares can be compared in Figure 6. While the lengths of rise times for slow flares can reach to 1400 s, they are not longer than 400 s for fast flares.

The comparison of another parameter is given in Figure 7. The flare amplitudes are seen in this figure. As can be seen, while the amplitudes of fast flares can reach to 4.0 mag, the amplitudes of slow flares can exceed 1.0 mag.

Around 61 fast and 79 slow flares were chosen among 321 flares observed in this study. The ratios of the flare decay time to the flare rise time were computed for both 61 fast and 79 slow flares. As a result, it is seen that the ratio is below 3.5 for each one of the 79 slow flares. On the other hand, the ratio is above 3.5 for each fast flare. The value 3.5 is considered a limit for these two types of flares. Considering the ratio of 3.5, the other 181 flares out of 321 were identified as slow and fast flares. When the results obtained from analyses of 140 flares were rechecked for the 321 flares, it was seen that the results are the same as previous ones.

3. RESULTS AND DISCUSSION

We observed 321 flares in the $U$-band observations of AD Leo, EV Lac, EQ Peg, and V1054 Oph. Examining 321 flares, 61 fast and 79 slow flares were identified for analyses. The $t$-test was used as an analysis method. Flare rise times were accepted as dependent variables, while flare equivalent durations were
taken as independent variables. The results obtained from the t-test analyses of the data show that there are distinct differences between the two types of flares. These differences are important properties because the models of white light flares observed in photoelectric photometry must support these properties to explain both types of flares.

The distributions of the equivalent durations were represented by linear fits given by Equations (3) and (4) for these types of flares. The slope of the linear fit is 1.109 for slow flares, which are low energy flares, and it is 1.227 for fast flares, which are high energy flares. The values are almost close to each other. It seems that the equivalent durations versus rise times increase in similar ways.

In the case of UV Ceti stars, when flare models are considered, it is seen that there are two main energy sources for flares (Gurzadian 1988; Benz & Güdel 2010). These depend on the thermal and non-thermal processes (Gurzadian 1988). Flares with small amplitude are generally the flares with low energy. The thermal processes are commonly dominant for these types of flares. On the other hand, the flares that have sudden rapid increases are more energetic events. The non-thermal processes are dominant for this type. Thus there is an energy difference between these two types of flares (Gurzadian 1988). When the averages of equivalent durations for two types of flares were computed in the logarithmic scale, it was found that the average of equivalent durations is 1.348 for slow flares and 2.255 for fast flares. The difference of 0.907 between these values in the logarithmic scale is equal to the 157.603 s difference between the equivalent durations. As can be seen from Equation (2), this difference between average equivalent durations affects the energies in the same way. Therefore, there is a difference of $\times 157.603$ between the energies of these two types of flares. This difference must be the difference mentioned by Gurzadian (1988).

The slopes of linear fits are almost close. On the other hand, if the y-intercept values of the linear fits are compared, it is seen that there is a 0.703 times difference in the logarithmic scale, while there is a 0.907 times difference between general averages. Also considering Figure 5, it is seen that equivalent durations of fast flares can increase more than slow flare equivalent durations toward long rise times. Some other effects should be involved in the fast flare process for long rise times. These effects can make fast flares seem more powerful than they actually are.

When the lengths of rise times for both types of flares are compared, it is seen that there is a difference between them. The lengths of rise times can reach to 1400 s for slow flares, but are not longer than 400 s for fast flares. In addition, when the flare amplitudes are examined for both types of flares, an adverse difference is seen according to rise times. While the amplitudes of slow flares reach to 1.0 mag at most, the amplitudes of fast flares can exceed 4.0 mag.

Finally, when the ratios of flare decay times to flare rise times are computed for two types of flares, the ratios never exceed 3.5 for all slow flares. On the other hand, the ratios are always above 3.5 for fast flares. It means that if the decay time of a flare is 3.5 times longer than its rise time at least, the flare is a fast flare. If not, the flare is a slow flare. Therefore, the type of an observed flare can be determined by considering this value of the ratio. In studies by Osawa et al. (1968), Oskanian (1969), Haro & Parsamian (1969), and Moffett (1974), in which they directly considered the shapes of flare light variations, the flares were classified into two types (fast flares and slow flares). For instance, according to Haro & Parsamian (1969), if the rise time of a flare is above 30 minutes, the flare is a slow flare. If not, it is a fast flare. However, it is shown in this study that there are some fast flares whose rise times are longer than the rise times of some slow flares. This is clearly shown in Table 3. This case indicates that a classification by considering only the rise time may not be correct. Nevertheless, Moffett (1974) separated flares into more than two groups such as classic, complex, spike, and flare events. On the other hand, according to our results of t-test analyses, neither only one parameter nor the shape of the light variation was enough to classify a flare. The flare equivalent durations as well as one more parameter should be taken into account in order to make such a classification.

The value 3.5, the ratio of flare decay times to flare rise times, can give an idea about the rate of energy emitting in a flare process. The rise times of flares have some limits for each type of flare. The maximum flare rise time is about 400 s for fast flares, while it can reach values over 1400 s for slow flares. However, the decay times can take any duration without limited values. Consequently, the ratio of flare decay times to flare rise times depends more on rise times than decay times. In the case of the rise time, the difference between two types of flares must be caused by whether the flare processes are thermal or non-thermal. We computed the duration as a rise time from the phase in which the brightness increases. An increase in the brightness is caused by an increase in the temperature of some region on the surface of the star. The flare rise time is an indicator of heating this region on the surface. Therefore, the ratio of flare decay times to flare rise times, so the values of 3.5, must be a critical value between thermal or non-thermal processes.

As can be seen from the models of Gurzadian (1988), the differences between flare durations and flare amplitudes are seen between two types of flares derived from the observed flares in this study. The difference between the amplitudes of slow and fast flares was given by Equation (22) in Gurzadian (1988). In the case of a flare amplitude, the result obtained in this study is in agreement with this equation.

Providing that the value 3.5 is a limit ratio for flare types, the fast flare rate is 63% of the 321 flares observed in this study, while the slow flare rate is 37%. It means that one in every three flares is a fast flare, while two out of three are slow flares. This result diverges from what Gurzadian (1988) stated. According to Gurzadian (1988), slow flares with low energies and low amplitudes make up 95% of all flares, and the remainder are fast flares. When looking individually over each star, the rate of flare types changes from star to star. The detected number of flares for AD Leo is 110 as can be seen from Table 2. The slow flare rate of AD Leo flares is 78%, while the rate of fast flares is 22%. The detected number of flares is 98 in the observation of EV Lac and 40 in the observation of V1054 Oph. The slow flare rates of both stars are 75%, while the fast flare rates are 25%. The EQ Peg number of flares is 78. The slow flare rate of these flares is 63% and the fast flare rate is 37%.

In this study, one of the remarkable points is the correlation coefficients of linear fits. As shown in Table 4, the correlation coefficient is 0.732 for the linear fit of the slow flare type and 0.476 for fast flares. Although the correlation coefficient of the linear fit to the distribution of equivalent durations versus rise times is in an acceptable level for slow flares, it is relatively lower for fast flares. Regression calculations show that the best fits are linear for the distribution of equivalent durations versus rise times in logarithmic scales. The correlation coefficients of other fits are not higher than linear correlation coefficients. In fact,
the correlation coefficient is lower for the fast flares due to the
distribution of their equivalent durations. As shown in Figure 5,
the equivalent durations of fast flares can take values in a wide
range toward the longer rise times. This must be due to the same
reason for differences between the y-intercept values and the
mean averages of equivalent durations of the two types of flares.
As discussed above, while the slopes of the fits are nearly close
to each other, there is a considerable difference between the
y-intercept values and the mean average of the equivalent
durations for the two types of flares. Consequently, all these
deviations are seen in fast flares. Magnetic reconnection is
dominant in this type of flare. A parameter in the magnetic
reconnection process causes some fast flares to be more powerful
than the expected values. Eventually, some fast flares become
more powerful than they would otherwise be, while some of
them are at expected energy levels. On the other hand, this
parameter in the magnetic reconnection process is not dominated
by slow flare processes, so the distribution of their equivalent
durations is not scattered. This must be why the correlation
coefficient of the fit is relatively higher for slow flares.

In this classification method, the complex flares are an
exceptional case. These flares must be composed of some different
flares. The complex flare should be decomposed into
component flares before classification. If the fast and slow flares
can be modeled, then using these models the complex flares can
be decomposed into component flares.

In conclusion, some parameters can be computed from flares
observed in photoelectric photometry and if the behaviors
between these parameters can be analyzed by suitable methods,
flare types can be determined. In this study, we analyzed the
distributions of equivalent durations versus flare rise times by
using a t-test. Finally, it is seen that using the ratios of flare
decay times to flare rise times, flares can be classified. Thus,
flares are classified into two types, as fast flares and slow flares.
It is seen that there are considerable differences between these
two types of flares. The differences and the similarities between
flare types are important in order to understand flare processes.
This provides new insight into modeling white light flares of
UV Ceti stars.

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