SATURATION LEVELS FOR WHITE-LIGHT FLARES OF FLARE STARS: VARIATION OF MINIMUM FLARE DURATION FOR SATURATION

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ABSTRACT

Taking into account results obtained from models and from statistical analyses of obtained parameters, we discuss flare activity levels and flare characteristics of five UV Ceti stars. We present the parameters of unpublished flares detected over two years of observations of V1005 Ori. We compare parameters of the U-band flares detected over several seasons of observations of AD Leo, EV Lac, EQ Peg, V1054 Oph, and V1005 Ori. Flare frequencies calculated for all program stars and maximum energy levels of the flares are compared, and we consider which is the most correct parameter as an indicator of flare activity levels. Using the One Phase Exponential Association function, the distributions of flare equivalent duration versus flare total duration are modeled for each program star. We use the Independent Samples t-Test in the statistical analyses of the parameters obtained from the models. The results reveal some properties of flare processes occurring on the surfaces of UV Ceti type stars. (1) Flare energies cannot be higher than a specific value regardless of the length of the flare total duration. This must be a saturation level for white-light flares occurring in flare processes observed in the U band. Thus, for the first time it is shown that white-light flares have a saturation in a specific energy range. (2) The span values, which are the difference between the equivalent durations of flares with the shortest and longest total durations, are almost equal for each star. (3) The half-life values, minimum flare durations for saturation, increase toward the later spectral types. (4) Both maximum total durations and maximum rise times computed from the observed flares decrease toward the later spectral types among the UV Ceti stars. According to the maximum energy levels obtained from the models, both EV Lac and EQ Peg are more active than the other three program stars, while AD Leo is the most active flare star according to the flare frequencies.

Key words: methods: data analysis – methods: statistical – stars: flare – stars: individual (V1005 Ori, AD Leo, V1054 Oph, EV Lac, EQ Peg)

1. INTRODUCTION

UV Ceti type stars are mostly pre-main-sequence stars coming to the zero-age main sequence (ZAMS) or stars at the ZAMS. Most of the red dwarfs in open clusters and associations are flare stars (Mizroyan 1990; Pigatto 1990). The number of flare stars in the clusters decreases with increasing cluster age. This is a reasonable scenario according to the Skumanich’s law (Skumanich 1972; Marcy & Chen 1992; Pettersen 1991; Stauffer 1991). A higher rotation rate gives rise to a higher flare activity level, leading to a higher mass loss via flare bursts. Previous studies indicate that the mass-loss rate of the Sun is about \(2 \times 10^{-13} M_\odot \text{yr}^{-1}\) (Gershberg 2005). However, this value for UV Ceti-type stars can reach a value of \(10^{-10} M_\odot \text{yr}^{-1}\) because of the flare activity. The high level of mass loss for these stars can explain the fact that they lose 98% of their angular momentum in their of main sequence lifetime (Mirzoyan 1990).

High mass loss due to magnetic flare activity has not been satisfactorily explained. The average energy of classical flares of the Sun is \(10^{26}-10^{27}\) erg. This rises to about \(10^{30}-10^{31}\) erg for two-ribbon flares, which are known to be the hardest flares on the Sun (Gershberg 2005; Benz & Güdel 2010). When flares of chromospherically active stars, known as RS CVn stars, are examined, it is seen that flare energies of these stars are about \(10^{31}\) erg (Haisch et al. 1987). However, observations made over 50 years show that flare energies of UV Ceti stars rise from \(10^{28}\) erg to \(10^{34}\) erg (Gershberg 2005). Moreover, when flare stars in young clusters such as the Pleiades cluster and Orion association are considered, their flare energies can reach \(10^{36}\) erg (Gershberg & Shakhovskaya 1983).

As can be seen from the literature, there are distinctive differences between flare energies of stars of different type. Nevertheless, although there are clear differences between the Sun and UV Ceti type stars regarding mass loss and flare energies, the flare activity of dMe stars is modeled on the process known as a solar flare event. In this case, it is accepted that the source of energy in these events is the magnetic reconnection process (Gershberg 2005; Hudson & Khan 1997). To properly understand all flare event processes for dMe stars, it could be useful to find all the similarities and differences between flare light curves by examining star to star. For instance, looking at flare energy spectra can be helpful as a first step. This distribution can show how flare energy range from one star to another. In this respect, both the distributions and levels of flare energy spectra of UV Ceti type stars have been examined in many studies, such as Gershberg (1972), Lacy et al. (1976), Walker (1981), Gershberg & Shakhovskaya (1983), Pettersen et al. (1984), and Mavridis & Avgoloupis (1986). For instance, flare energy spectra have been studied by Gershberg (1972) for AD Leo, EV Lac, UV Cet, and YZ CMi. In another study made by Gershberg & Shakhovskaya (1983), flare energy spectra for many stars in the Galactic field have been compared with those of stars from the Pleiades cluster and Orion association. As seen from Figure 2(b) of Gershberg & Shakhovskaya (1983), the flare energy spectra for the stars of the Orion association are located at much higher levels than those from other stars. The Pleiades stars are located below those of the Orion association.
Finally, the stars from the Galactic field are located below these. This distinctive separation of flare energies of these stars from different sources shows that there is something different in their flare process. It appears that the differences between the levels of the flare energy spectra are due to different ages. On the other hand, there is also some separation among the stars located in the Galactic field.

All these variations among the different stars and star groups might be due to the saturation level of white-light flares detected from UV Ceti-type stars. It is observed that some parameters of magnetic activity can reach saturation (Gershberg et al. 1999; Skumanich & McGregor 1986; Vilhu & Rucinski 1983; Vilhu et al. 1986; Doyle 1996a, 1996b). White-light flares are detected in some large active regions such as compact and two-ribbon flares occurring on the surface of the Sun (Rodonó 1990; Benz & Gudel 2010). We expect that the energies or the flare-equivalent durations can reach saturation. The analyses of some large flare data sets confirm this expectation. If a saturation level can be found, it will be a guide to modeling the white-light flares. However, the data sets used in the analyses are important. They need to be comprised of parameters derived with the same method, and from flares detected with the same optical system. Otherwise, some artificial variations and differences can occur between the sets. To avoid this problem, we used large data sets, which comprised parameters derived with the same method and the same optical system.

Flare frequencies can be another useful parameter to aid understanding of the flare process. In some studies such as Pettersen et al. (1983), Ishida et al. (1991), and Leto et al. (1997), flare frequencies have been examined. Two flare frequencies have generally been calculated in these studies. As is seen from the literature, flare energies and frequencies vary from star to star. To understand the complete flare processes, the cause of these variations should be determined. In this regard, it must be established whether these differences are related to physical parameters such as mass and age, or are directly due to different flare processes.

In this study, we compared flare parameters from five UV Ceti-type stars given in Table 1. The physical parameters in the table (such as mass, radius, and distance) are taken from Gershberg et al. (1999). According to spatial velocities taken from Montes et al. (2001), it is seen that AD Leo is a red dwarf member of the Castor Moving Group, whose age is about 200 Myr. In the same way, according to spatial velocities, EV Lac is seen to be a member of the 300 Myr old Ursa Major Group, known as the Sirius Supercluster. V1005 Ori, whose first flare light curve was obtained by Shakhovskaya (1974), is a member of the 35 Myr old IC 2391 Supercluster (Montes et al. 2001). According to another study made by Veeder (1974), these three stars also appear to belong to the young disk population of the Galaxy. EQ Peg, at a distance of 6.58 pc, is classified as a metal-rich star and it belongs to the young disk population of the Galaxy. V1054 Oph is a triple-lined spectroscopic system known as Giese 644 (= Wolf 630 + Wolf629AAb) at a distance of 6.5 pc. V1054 Oph is classified as a metal-rich star and a member of the old disk population of the Galaxy (Veeder 1974; Fleming et al. 1995). The flare stars whose flare parameters are compared in this study are quite young stars, except for V1054 Oph. The masses were derived for each component of Wolf 629AAb by Mazeh et al. (2001), and were shown to be 0.41 M☉ for Wolf 629A, 0.336 M☉ for Wolf 629B, and 0.304 M☉ for Wolf 629Bb. In addition, Mazeh et al. (2001) demonstrated that the age of the system is about 5 Gyr.

### Table 1

| Star             | Distance (pc) | Mass (M☉) | Radius (R☉) |
|------------------|---------------|-----------|-------------|
| AD Leo           | 4.9           | 0.28      | 0.54        |
| EV Lac           | 5             | 0.18      | 0.39        |
| EQ Peg           | 6.2           | 0.28      | 0.58        |
| V1054 Oph        | 5.7           | 0.42      | 0.76        |
| V1005 Ori        | 26.7          | ...       | 0.7         |

### 2. OBSERVATIONS AND ANALYSES

#### 2.1. Observations

Observations were acquired with the High-Speed Three-Channel Photometer attached to the 48 cm Cassegrain-type telescope at Ege University Observatory. Using a tracking star set in the second channel of the photometer, the observations of the variable star were continued in the standard Johnson U band with an exposure time between 2 and 10 s. The basic parameters of all the program stars (such as standard V magnitudes and B – V colors) are given in Table 2, and were taken from Dal & Evren (2010) for AD Leo, EV Lac, EQ Peg, and V1054 Oph. Although the program and comparison stars are so close in the plane of 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 arrested differential magnitudes, in the sense of variable minus comparison, were transformed to the standard system using procedures outlined by Hardie (1962). The standard stars are listed in the catalogs of Landolt (1983, 1992). Heliocentric corrections were applied to the observation times. The standard deviation of each observation acquired in the standard Johnson U band was about 0.15 on each night. Observational reports of all the program stars are given in Table 3. The differential magnitudes in the sense of comparison minus check stars were carefully checked for each night. The comparison and check stars were found to be constant in brightness during the period of observation. Equivalent durations and energies of all the flares were computed from photoelectric observations using Equations (1) and (2) taken from Gershberg (1972):

\[ P = \int [(I_{\text{flare}} - I_0)/I_0]dt, \]  \hspace{1cm} (1)

where \( I_0 \) is the flux of the star in the observing band while in the quiet state, and \( I \) is the intensity at the moment of flare:

\[ E = P \times L, \]  \hspace{1cm} (2)

where \( E \) is the energy, \( P \) is the flare-equivalent duration in the observing band, and \( L \) is the intensity in the observing band while the star is in the quiet state. For each observed flare, the HJD of flare maximum moment, flare rise and decay time, flare amplitude, flare-equivalent duration, and their energies were calculated. In the calculations, the quiescent level, in which there is no flare or other variability, was accepted as the basic level of the nightly light curves. All parameters were computed taking this level into account.

Some flares had several peaks. In this case, the maximum point of the flare was taken to be the peak that was highest, and close to the initial point. Instead of the flare energy, flare-equivalent duration was used in the comparison, because of the luminosity term in Equation (2). The luminosities of stars
Table 2
Basic Parameters for the Targets Studied and Their Comparison (C1) and Check (C2) Stars

| Star          | $V$ (mag) | $B-V$ (mag) |
|---------------|-----------|-------------|
| V1005 Ori     | 10.090    | 1.307       |
| C1 = BD+01 870| 8.800     | 1.162       |
| C2 = HD 31452 | 9.990     | 0.920       |
| AD Leo        | 9.388     | 1.498       |
| C1 = HD 89772 | 8.967     | 1.246       |
| C2 = HD 89471 | 7.778     | 1.342       |
| EV Lac        | 10.313    | 1.554       |
| C1 = HD 215576| 9.227     | 1.197       |
| C2 = HD 215488| 10.037    | 0.881       |
| EQ Peg        | 10.170    | 1.574       |
| C1 = SAO 108666| 9.598    | 0.745       |
| C2 = SAO 91312| 9.050     | 1.040       |
| V1054 Oph     | 8.996     | 1.552       |
| C1 = HD 152678| 7.976     | 1.549       |
| C2 = SAO 141448| 9.978    | 0.805       |

Table 3
Observational Reports of the Program Star for Each Observing Season

| Star          | Season       | HJD Interval (+24 00000) | Number of Night | Observing Duration (hr) | Flare Number |
|---------------|--------------|--------------------------|-----------------|-------------------------|--------------|
| V1005 Ori     | 2004–2005    | 53353–53453              | 9               | 28.13                   | 10           |
|               | 2005–2006    | 53673–53769              | 9               | 26.45                   | 31           |

with different spectral types have large differences. Although the equivalent durations of two flares detected from two stars of different spectral types are the same, the calculated energies of these flares are different due to the different luminosities of these spectral types. Therefore, we could not use these flare energies in the same analysis. On the other hand, flare-equivalent duration depends only on the power of the flare. Another reason for using equivalent duration is that the given distances of the same star in different studies are quite different. These differences cause the calculated luminosities to be different.

In Figure 1, a fast flare sample detected in observations of V1005 Ori on 2005 January 6 is seen. According to a rule devised by Dal & Evren (2010), this flare is classified as a fast flare. Two consecutive flares detected on 2005 January 10 are shown in Figure 2. These flares are classified as slow flares with respect to the same rule. The consecutive flare samples of V1005 Ori are shown in Figure 3; these flares were detected on 2005 December 29.

Using the method of Dal & Evren (2010), all parameters are calculated for each flare detected in the observations of V1005 Ori. The calculated parameters for 41 $U$-band flares are given in Table 4. The columns of the table are the date of observation, HJD of flare maximum, flare rise time, flare decay time, equivalent duration, flare amplitude, and flare type.

2.2. Analyses

V1005 Ori flare data were combined with a data set that included 321 $U$-band flares detected from other stars (AD Leo, EV Lac, EQ Peg, and V1054 Oph). The parameters of the 321 $U$-band flares detected from these stars were presented by Dal & Evren (2010). Using this large data set, comprising in total 362 $U$-band flares, program stars were compared with each other in the analyses to find out whether there is any difference between their flare activity behaviors. In this regard, as mentioned above, the data used in the analyses are important. The data must be comprised of parameters determined by the same method. In addition, the flares must be observed with the same optical systems. There are large data sets including $U$-band flares in the literature, such as those of Moffett (1974), and Ishida et al. (1991). On the other hand, the methods used to determine the parameters of the detected flares are not the same in these studies and there are some differences between the optical systems. This is why we used the data obtained in this study along with the data of Dal & Evren (2010). All the parameters in these data sets were determined by the same method and all the flares were detected with the same optical system.

When the distribution of flare-equivalent durations on a logarithmic scale versus flare total duration is examined, it is seen that flare-equivalent duration is below a limiting value no matter how long the flare total duration is. In addition, when we
compare stars with each other, it is clear that the energy limiting value is different for each star.

To model the distributions, the most appropriate function was sought. Using the SPSS V17.0 (Green et al. 1999) and GraphPad Prism V5.02 (Dawson & Trapp 2004) software, regression calculations showed that the best fit is the One Phase Exponential Association (hereafter OPEA) for the distributions of flare-equivalent duration. The OPEA function (Motulsky 2007; Spanier & Oldham 1987) is a special exponential function which has a Plateau term, as seen in the distributions of flare-equivalent durations:

\[
y = y_0 + (\text{Plateau} - y_0) \times (1 - e^{-k \times x}), \tag{3}
\]

where \(y\) is the flare-equivalent duration on a logarithmic scale, \(x\) is the flare total duration, and \(y_0\) is the flare-equivalent duration in on a logarithmic scale for the least total duration. In other words, \(y_0\) is the least equivalent duration occurring in a flare for a star. The value of \(y_0\) depends on the brightness of the target and sensitivity of the optical system. The value of \(\text{Plateau}\) is the upper limit of the equivalent duration, which can occur in a flare for a star. This parameter can be identified as a saturation level for flare activity observed in the \(U\) band. According to Equation (2), the value of \(\text{Plateau}\) depends only on the energy of flares occurring on the star. According to the definition of the OPEA function, the parameter \(k\) in Equation (3) is a constant depending on the \(x\) values. Using the least-squares method, for each star the distributions were modeled by the OPEA function.

All the distributions and their models with 95% confidence intervals are shown in Figure 4.

The parameters derived from the OPEA models are given in Table 5 for all the stars. Star name, \(B - V\) index, \(\text{Plateau, } y_0\) and \(k\) values are listed in the table. The span value and half-life value are given in the last two columns. \(B - V\) indices are also found in this study. The span value is the difference between the values of \(\text{Plateau}\) and \(y_0\). The half-life value is half of the first \(x\) values, where the model starts to give the \(\text{Plateau}\) values for a star. In other words, it is half of the flare total duration, where flares with the highest energy start to appear. The half-life value is the minimum value of the flare total duration, which is required for the saturation level.

| Table 4 Calculated Parameters of Flares Detected in the Observations of V1005 Ori |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Date            | HD of Maximum (+24 00000) | Flare Rise Time (s) | Flare Decay Time (s) | Equivalent Duration (s) | Energy (erg) | Amplitude (mag) | Flare Type |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------|
| 2004 Dec 13     | 53353.42334     | 420             | 375             | 98              | 1.6799E+33     | 0.304           | Slow      |
| 2004 Dec 13     | 53353.43480     | 30              | 75              | 5               | 7.9712E+31     | 0.271           | Slow      |
| 2004 Dec 13     | 53353.44452     | 30              | 510             | 103             | 1.7617E+33     | 0.121           | Fast      |
| 2005 Jan 6      | 53377.31547     | 15              | 15              | 4               | 6.6193E+31     | 0.158           | Fast      |
| 2005 Jan 6      | 53377.36773     | 345             | 2055            | 980             | 1.6731E+34     | 0.919           | Fast      |
| 2005 Jan 10     | 53381.37637     | 60              | 765             | 276             | 4.7061E+33     | 0.834           | Fast      |
| 2005 Jan 10     | 53381.41977     | 450             | 1995            | 427             | 7.2863E+33     | 0.221           | Fast      |
| 2005 Jan 12     | 53383.26550     | 15              | 60              | 4               | 6.0373E+31     | 0.215           | Fast      |
| 2005 Feb 12     | 53414.34290     | 15              | 90              | 9               | 1.5474E+32     | 0.212           | Fast      |
| 2005 Feb 12     | 53414.35470     | 15              | 15              | 4               | 6.7371E+31     | 0.215           | Slow      |
Figure 4. Distributions of flare-equivalent duration on a logarithmic scale vs. flare total duration for each program star (a), (b), (c), (d), (e). Filled circles represent equivalent durations computed from observed flares. The lines represent the models identified with Equation (3) computed using the least-squares method. The dotted lines represent 95% confidence intervals for the models for each star. In panel (f), all models derived for each star are compared.

Table 5

Parameters Derived from the OPEA Model, which were Derived Using the Least-Squares Method

| Star     | $B - V$ (mag) | Plateau $y_0$ ($\log P_u$) | Span Value Half-life (log $P_u$) | $k$ (Total Duration) | Mean Equivalent Duration (log $P_u$) |
|----------|---------------|-----------------------------|---------------------------------|-----------------------|-------------------------------------|
| V1005 Ori | 1.307         | 2.637 ± 0.074               | 0.428 ± 0.198                   | 0.003063 ± 0.000623   | 2.209 ± 0.193                      |
| AD Leo   | 1.498         | 2.527 ± 0.086               | 0.370 ± 0.054                   | 0.002738 ± 0.000341   | 2.158 ± 0.089                      |
| V1054 Oph | 1.552         | 2.462 ± 0.105               | 0.385 ± 0.101                   | 0.002305 ± 0.000435   | 2.077 ± 0.119                      |
| EV Lac   | 1.554         | 3.014 ± 0.084               | 0.698 ± 0.057                   | 0.002404 ± 0.000250   | 2.316 ± 0.087                      |
| EQ Peg   | 1.574         | 2.935 ± 0.091               | 0.859 ± 0.081                   | 0.002074 ± 0.000272   | 2.076 ± 0.094                      |

The variation of $Plateau$ values, which are listed in Table 5, and the mean values of equivalent durations, which are given in Table 6, are plotted versus the $B - V$ index of each star and are shown in Figure 5. As expected, both parameters exhibit the same variations with little difference in their levels. In the figure, the mean equivalent durations and the $Plateau$ values...
Figure 5. Variation of both the Plateau parameter (a) and the mean equivalent duration (b) vs. the $B-V$ index of the stars. The dotted lines represent the linear fits for the first three points, which are used to indicate the decrease of both values of the Plateau and the mean equivalent duration.

decrease with increasing $B-V$ index for three stars, namely V1005 Ori, AD Leo, and V1054 Oph. On the other hand, these two parameters are dramatically higher for two stars, EV Lac and EQ Peg, which are the reddest among the five. In the figure, the decrease of the first three values is shown as linear fits for both parameters. The variation of Plateau values indicates that the saturation level of flare activity can change. Moreover, the saturation levels of the reddest stars among the five are substantially higher than those of the other stars.

The variation of the other parameters derived from the OPEA models are shown versus the $B-V$ index in Figure 6. The variation of the parameter $y_0$ is plotted in panel (a) of this figure. Although the parameter $y_0$ depends both on the brightness of the target and the sensitivity of the observing system in a general manner due to the standard deviations of the observations, here $y_0$ exhibits a dramatic increase for two stars, which are located toward the reddest edge. This means that the flare energy for the least total duration of flares is higher for stars that are located toward the reddest edge of M type. In panel (b), the variation of the span values, which is the difference between $y_0$ and Plateau values obtained from model curves, is plotted versus $B-V$ index. According to the models, the span value shows no important variation versus $B-V$ index. In panel (c), the variation of half-life values is plotted versus $B-V$ index. The regression calculations indicated that the polynomial function is the best fit, which is shown by the dotted line in the figure, for this variation of the value. As seen from the panel, the half-life values increase toward the reddest M stars.

When the 362 flares observed from the five stars are examined, it is observed that the longest flare total durations vary from star to star. From Figure 4, the total duration of the longest flare is 2940 s for EV Lac and 3180 s for EQ Peg, while it is 5236 s for V1005 Ori, and reaches 4164 s for AD Leo. The longest flare total duration is about 3270 s for V1054 Oph. From Figure 7, the observed maximum flare total durations decrease toward the later spectral types. The maximum flare rise time was also computed for each star. For V1005 Ori, AD Leo, V1054 Oph, EV Lac, and EQ Peg, the maximum rise times were 2036 s, 1212 s, 1460 s, 840 s, and 1230 s, respectively. The variation of all these times is also shown in Figure 7.

Two different flare frequencies of stars were computed for each season to examine flare activity levels. These flare
frequencies are (Ishida et al. 1991):

\[ N_1 = \frac{\Sigma f}{\Sigma T_t}, \quad (4) \]

\[ N_2 = \frac{\Sigma P_u}{\Sigma T_t}, \quad (5) \]

where \( \Sigma T_t \) is the total observing duration, \( \Sigma f \) is the total number of flares obtained in a season, and \( \Sigma P_u \) is the total equivalent duration obtained from all the flares detected in that observing season. \( N_1 \) and \( N_2 \) are the flare frequencies. All computed frequencies are listed in Table 7. According to the results, higher flare frequencies are seen in AD Leo.

### 3. RESULTS AND DISCUSSION

The flare energy, which is expressed by Equation (2) given by Gershberg (1972), has generally been used to examine the level of flare activity in many studies (see, e.g., Mazeh et al. 2001; Lacy et al. 1976; Walker 1981; Gershberg & Shaklovskaya 1983; Pettersen et al. 1984; Mavridis & Avgoloupis 1986). The luminosity parameter \( L \) occurs in the expression of the energy \( E \), as in all these and other studies. The luminosity \( L \) is different for each star. Although there are small differences among the masses of M dwarfs, the luminosities of the two M dwarfs, whose masses are very close to each other, can be dramatically different due to their position in the H–R diagram. This means that the computed energies of flares are very different from each other, even if the light variation of the flares occurring on these two stars are the same. Because of this, the equivalent durations \( P \) were used instead of energy \( E \) in this study. If there is a difference in the equivalent durations of the flares, it is reflected in the energies.

In the analyses, the distributions of flare-equivalent durations versus flare total duration were modeled by the OPEA function expressed by Equation (3) for all stars in the program. When the models are compared, some differences are observed among the stars. As seen in Figures 4(f) and 5(a), the Plateau parameter, which gives the maximum equivalent duration level for flares on a star, changes from one star to another. From Figure 4(f), the distributions of the equivalent durations on a logarithmic scale versus flare total duration for EV Lac and EQ Peg are different from those of the other three stars. The maximum equivalent durations seen in these two stars are as high as 0.5 times on the logarithmic scale. This difference on the logarithmic scale is equal to 683 times difference in energy. This means that, for example, the energy of an EV Lac flare is 683 times higher than the energy of an AD Leo flare on average. In addition, the energy of a flare occurring on AD Leo is never higher than the energy of an EV Lac flare, no matter how long the total duration of the AD Leo flare. This result is confirmed by the \( t \)-Test. We used the flares whose equivalent durations on the logarithmic scale are located in the Plateau phase in the OPEA models, in the \( t \)-Test. In this regard, the aim is to compare the equivalent durations of flares, whose energies are independent of the lengths of their total duration. The results of the \( t \)-Test analyses are shown in the Figure 5(b). From this figure, the mean averages of equivalent durations computed by the \( t \)-Test are close to the Plateau values derived from the OPEA models. The mean averages of maximum equivalent duration for flares of EV Lac and EQ Peg are distinctly higher than the averages computed for the other three stars. On the other hand, the mean averages of equivalent duration are different for each star.

As mentioned above, some parameters of the chromospheric magnetic activity can reach saturation (Gershberg 2005; Skumanich & McGregor 1986; Vilhu & Rucinski 1983; Vilhu et al. 1986; Doyle 1996a, 1996b). In the case of a white-light flare, we expect that the energies or the flare-equivalent durations can reach saturation, because these white-light flares are detected in some large active regions such as compact and two-ribbon flares occurring on the surface of the Sun (Rodonó 1990; Benz & Güdel 2010). Consequently, according to this approach, the Plateau value must be a saturation level (or an indicator at least) for white-light flares. In the analyses, we used data obtained by the same method and the same optical system. In addition, we used the flare-equivalent durations instead of the flare energies. Therefore, the derived Plateau values depend only on the power of the white-light flares. Considering the

![Figure 7. Variation of maximum flare rise time (a) and maximum flare total duration (b) vs. the B – V index. The dotted lines are their linear fit.](image-url)
Plateau values, it is seen that the power of the flare has a limit for a star. The flare-equivalent durations cannot be higher than a particular value no matter how long the flare total duration is. Instead of the flare duration, some other parameters, such as magnetic field flux and/or particle density in the volumes of the flare processes, must be more efficient in determining the power of the flares. Considering thermal and non-thermal flare events, both these parameters can be more efficient.

Gurzadian (1977, 1988) developed a hypothesis called the fast electron hypothesis, in which the source of the white-light flares on the surfaces of UV Ceti stars is a non-thermal process such as the spontaneous appearance of fast electrons on the surface of the flare stars. In this hypothesis, the particle density in the volumes of the flare processes must be more efficient than the magnetic field in determining the power of the white-light flares. Gurzadian (1988) demonstrated that the inverse Compton effect, i.e., non-thermal interactions of infrared photons with fast electrons, causes some radiative losses. It is possible that the inverse Compton effect can be more efficient after a specific flare duration for a UV Ceti star, and this effect can limit the observed flare-equivalent duration (and energy) of a detected flare. However, considering the whole flare process, it should be noted that the particle density in the volumes depends on magnetic field flux in some respects. The source of this flux is particles accelerated by the magnetic field (Benz & Güdel 2010; Gershberg 2005). In addition, the magnetic field flux in the volumes is more efficient than the particle density for high energy patterns of the flare processes, such as soft X-ray or radio intensities (Gershberg 2005).

In contrast, Doyle (1996a, 1996b) suggested that the saturation in the active stars does not have to be related to the filling factor of magnetic structures on the stellar surfaces or the dynamo mechanism under the surface. It can be related to some radiative losses in the chromosphere, where the temperature and density are increasing in the case of fast rotation. This phenomenon, can occur in the chromosphere due to the flare process instead of fast rotation, and this causes the Plateau phase to occur in the distributions of flare-equivalent duration versus flare total duration. On the other hand, the Plateau phase cannot be due to some radiative losses in the chromosphere with increasing temperature and density. This is because Grinin (1983) demonstrated the effects of radiative losses in the chromosphere on the white-light photometry of the flares. According to Grinin (1983), the negative H opacity in the chromosphere causes the radiative losses, and these are seen as pre-flare dips in the light curves of the white-light flares. In addition, when the results are considered, it is seen that the Plateau values vary from one star to the next. This indicates that some parameters, which give rise to the Plateau in the distributions of flare-equivalent durations, or their efficacies, are changing from star to star. Moreover, in the case of EV Lac and EQ Peg, there is a distinctive difference. The efficacies of these parameters (or the parameters themselves) must be dramatically changed for these stars.

In future, the cause(s) of the Plateau phases should be examined by the synchronous observations in the radio, optic, and X-ray regions of the spectrum. In these studies, we recommend that some tests should be made. When the energy of a white-light flare detected with optical photometry reaches saturation level, it should be investigated whether or not the energy reaches saturation in the radio or X-ray observation. If the energy reaches saturation in the radio or X-ray observation, this indicates that the cause of the saturation is generally the magnetic field. This is because the energy source in the radio or X-ray is generally magnetic reconnection. If the energy does not reach saturation in the synchronous optical photometry, it means that the particle density in the volumes is more efficient in determining the power of the flares in the optical part of the spectrum.

However, it is worth noting that the known very weak correlation of the optical and radio flares in the UV Cet type variables makes such an experiment difficult to realize. Moreover, the attribution of the flares in saturation regions to white-light flares seems to be weakly proved. On the Sun, such flares are selected with spectroscopic observations when there is a strong continuum. On stars, multicolor observations allow the definition of a phase when blackbody radiation that is a continuum, dominates (Zhiyaev et al. 2007).

When the variation of the parameter \( y_0 \) is examined, from Figure 6(a), it is seen to be changing from star to star. Like the parameter Plateau, \( y_0 \) parameters of EV Lac and EQ Peg are rather higher than those of the other stars. \( y_0 \) parameters of the other three stars are almost equal to each other. Actually, \( y_0 \) depends on both the brightness of the target and the sensitivity of the observing system. On the other hand, considering that the brightness of all the targets is almost equal to each other and all of them were observed with the same system at almost the same time, the variation of \( y_0 \) from star to star is close to the real behavior.

The difference between Plateau and \( y_0 \), which is derived from the distribution modeled by Equation (3), is listed in Table 5 as the span value. Figure 6(b) shows no regular variation in the behavior of this parameter versus \( B - V \) index. This is important because it means that the difference between Plateau and \( y_0 \) is constant along all \( B - V \) indices of M type with respect to the five stars. The similarity of span value for all program stars shows that the difference between \( y_0 \) of the stars is exactly that between the Plateau values. This indicates that even if the conditions in which the flares occur, and thus the energies of the flares change, the difference between minimum and maximum energies is stable in the flare mechanism.

The variation of half-life value, which is an indicator of the minimum flare total duration required for maximum energy to occur, is seen in Figure 6(c). According to this variation, the values of half-life value increase toward higher \( B - V \) indices. This means that the minimum total duration, which is required for the flares to emit the maximum energy in the flare mechanisms, increases toward the later spectral types among the M-type stars. Consequently, this variation indicates that longer flare total durations are needed to reach saturation level toward the later spectral types among M dwarfs. Like the variation of the Plateau value versus \( B - V \) color index, the variation of half-life value must be considered to model the white-light flares detected from UV Ceti-type stars.

The maximum flare total duration seen among the flares for each star 2940 s for EV Lac and 3180 s for EQ Peg. It is 5236 s for V1005 Ori and 4164 s for AD Leo, while it is about 3270 s for V1054 Oph. Maximum flare total durations seen in flares of UV Ceti stars decrease toward the later spectral types among the M stars as seen in Figure 7. Like flare total durations, the maximum rise times are 2036 s, 1212 s, 1460 s, 840 s, and 1230 s for V1005 Ori, AD Leo, V1054 Oph, EV Lac, and EQ Peg, respectively. The variation of all these times is also shown in Figure 7; both maximum rise time and total duration decrease toward the later spectral types.

As a result, four important properties can be summarized for the flare processes occurring on UV Ceti-type stars. (1) Flare energies increase with flare total duration up to a specific total...
duration value, and then the energies are constant no matter how long the flare total duration is. (2) The differences between minimum and maximum energies of flares are constant and the same for all stars. (3) The minimum total durations, which are needed for the flares to emit the maximum energy, increase toward the later spectral types. (4) Maximum flare rise time and total duration decrease toward the later spectral types.

Two flare frequencies expressed by Equations (4) and (5) have been used to identify the flare activity levels in many studies. Researchers have used these frequencies to determine whether flare activity of UV Ceti stars exhibits any cyclic variation. Assuming that all the flares occurring on the stars are observed, \( N_1 \) is an indicator of flare number obtained in unit-time, as expressed by Equation (4). However, according to Equation (5), \( N_2 \) is an indicator of the mean equivalent duration average obtained in unit-time (Ishida et al. 1991). In brief, \( N_1 \) refers to how many flares occur on a star, while \( N_2 \) refers to how energetic these flare are.

In this study, both flare frequencies of \( N_1 \) and \( N_2 \) were computed season-to-season for each program star, and are listed in Table 7. The \( N_1 \) frequency of AD Leo is close to the 1.0 in 2005. It means that one flare occurred on AD Leo per hour at least. The \( N_2 \) frequency of the star was computed as 0.086. Considering the values obtained for each season and each star, this value of \( N_2 \) indicates that the flares occurring on AD Leo were powerful in 2005. The \( N_1 \) and \( N_2 \) frequencies are in agreement with each other in 2005. Conversely, \( N_1 \) is 1.331, while \( N_2 \) is 0.012 in 2006. \( N_1 \) is higher than 1.0, and this can be accepted as the highest value of \( N_1 \), but \( N_2 \) is not high. Although many flares were able to occur on AD Leo in 2006, their energies were not as high as expected values, as occurred in 2005. According to the value of \( N_2 \), the flare activity level of AD Leo was not high. This is debatable. As with AD Leo, some similar cases are seen in the other program stars. In the literature, both \( N_1 \) and \( N_2 \) frequencies are accepted as indicators of the flare activity level. For example, Mavridis & Avgoloupis (1986) computed both \( N_1 \) and \( N_2 \). Examining the distribution of these parameters versus time, they demonstrated that EV Lac had a flare activity cycle of five years.

According to Equation (5), \( N_2 \) depends on equivalent duration, in other words, energy. So, it is expected that \( N_2 \) can behave like the Plateau or the mean average of the equivalent durations. \( N_2 \) frequencies of EV Lac and EQ Peg are expected to be higher than the same frequencies of the other stars. However, the frequencies of these two stars are almost the same, with no clear difference between them.

According to all these results, the parameters of the Plateau and the mean average of the equivalent durations seem to be useful in determining the flare activity levels. We assume that it is the most active star that has the highest Plateau and mean parameters.

On the other hand, if the differences seen between the values of the Plateau or the mean average of the equivalent durations between the program stars had been caused by the age of the stars, it would be expected that V1005 Ori was the most active star according to Skumanich (1972). This is because V1005 Ori is a member of the IC 2391 Supercluster, which is 30–35 Myr old (Montes et al. 2001). Considering that all other stars are almost the same age apart from V1054 Oph, whose age is 5 Gyr, the difference can be caused by rapid rotation or binarity (Veeder 1974; Fleming et al. 1995; Montes et al. 2001). The equatorial rotational velocity of EV Lac is 4 km s\(^{-1}\) and it is between 5–5.8 km s\(^{-1}\) for AD Leo (Marcy & Chen 1992; Pettersen 1991). Conversely, the equatorial rotational velocity of V1005 Ori is 29.6 km s\(^{-1}\) (Eker et al. 2008). Assuming that Skumanich’s law is acceptable for the flare activity of UV Ceti stars, as in the case of chromospheric activity, the values of the Plateau or the mean average of the equivalent durations must be higher for stars which are rapidly rotating. However, according to our results, this is not a common rule. Beside this, EV Lac, AD Leo, and V1005 Ori are single stars, while there is a visual companion of EQ Peg, and V1054 Oph is a system composed of six stars (Pettersen 1991). Therefore, if binarity or multiplicity causes flare activity levels to increase, the most active flare star should be V1054 Oph.

We analyzed data obtained in three observing seasons from the observations of five stars, and have arrived to some clear results. These results are derived from both the OPEA model and the computed flare frequencies. The properties obtained regarding flare processes occurring on UV Ceti-type stars are important for the understanding of the general flare process for stellar flare activity. In this respect, extending the \( B – V \) range of program stars is required to obtain more data, which should be obtained from many different stars and flare patrols spanning many years, in order to obtain more reliable results.

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