FAST *UBVRI* COLORIMETRY OF STELLAR FLARES ON EV LACERTAE

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БЫСТРАЯ *UBVRI*-КОЛОРИМЕТРИЯ ЗВЕЗДНЫХ ВСПЫШЕК EV LACERTAE, Жиляев Б., Романюк Я., Святогоров О., Верлюк И., Алексеев И., Ловкая М., Авголоупис С., Контадакис М., Сейрадакис Дж., Антов А., Константинова-Антова Р. – Мы сообщаем о первых результатах колориметрического анализа вспышек EV Lac, основанного на *UBVRI*-данных, полученных в течение кампании синхронных наблюдений нескольких обсерваторий в сентябре 1998 г. Цветные характеристики вспышек и недавно обнаруженных высокочастотных колебаний блеска (HFO) находятся в центре внимания этой работы. Колориметрический анализ был выполнен с помощью временных цветовых треков, начиная с самой ранней стадии развития вспышки. Эта методика иллюстрируется на примере относительно сильной вспышки EV Lac 11 сентября 1998 г. Использовалась техника цифровой фильтрации, чтобы оценить: 1) колор-индексы как главной кривой блеска вспышки, так и HFO, 2) их поведение во времени в течение всей продолжительности вспышки. Было найдено, что колор-индексы главной кривой блеска вспышки значительно отличаются от таковых для быстрых колебаний. Первые демонстрируют сглаженные формы. В отличие от этого колор-индексы HFO сильно переменны, в особенности на стадии возрастания блеска. Благодаря HFO цвет вспышки колеблется от глубоко красного до экстремально синего в течение нескольких секунд. Когда вспышка достигла $U \approx -0.8$ зв. вел., цветные треки переместились в область цветных диаграмм, занятых водородной плазмой, оптически толстой в бальмеровском континууме.

Here we report first results of colorimetric analysis of the flare star EV Lac based on the $UBVRI$ data obtained during the course of many-site synchronous monitoring in 1998 September. The color characteristics of flares and small-scale high-frequency oscillations (HFO) recently discovered are in the focus of this work. Colorimetric analysis had been performed with the help of color time tracks, as from the earliest phase of the flare development. This technique is illustrated by the example of a relatively strong flare event of EV Lac on September 11, 1998. The digital filtering technique was used to evaluate: 1) the color indices of both the main flare light curves and HFO, 2) their time behavior during the flare lifetime. It is found that the color indices of the main outburst light curves differ significantly from those of rapid oscillations. The first shows smooth forms. In contrast to this, the corresponding HFO indices are greatly variable, in particular for the ascending part of a burst. On account of HFO the flare color oscillates from deep red to extremely blue on a time scale of seconds. When the flare grew to $\Delta U \simeq -0.8$ mag, color tracks were evolved into the region of color-color diagrams occupied by hydrogen plasma which is optically thick at the Balmer continuum.

INTRODUCTION

The many-site multi-channel simultaneous monitoring of the red dwarf flare star EV Lac was carried out from four separate sites in September – October 1998 [1]. These observations have confirmed the reality of rapid optical brightness oscillations during a significant part of the flare lifetime [6], as was discovered, for the first time, by Rodonó [4] in the Hyades flare star HII 2411. So far it was possible to estimate the color indices of pure flare radiation for strong enough flares nearly their brightness maximum. Infancy of flare development lives in the shadow. Our synchronous observations provide information of high quality on the pure flare radiation as well as on color dynamics and associated rapid optical oscillations practically throughout the flare lifetime. Our approaches and the digital filtering technique allow us to look in the earliest phase of the flare development. An estimation of the color characteristics of the main outburst light curve as well as of rapid oscillations are the primary goals of this paper.

METHODS

The Synchronous Network of distant Telescopes (SNT) project supplies the capabilities to study small amplitude phenomena on the shortest time scales. Fig. 1 shows portions of the high-pass filtered U and R data and of the low-pass filtered U light curve from the sets of EV Lac measurements obtained with the 1.25-m telescope in Crimea. This flare event has been observed synchronously with the 30-inch telescope at the Stephanion Observatory in Greece too. Time variations in HFO were found coincided within experimental errors [6]. Now we have a good chance of following its characteristics, including color variations, during the whole flare light curve. A quantitative colorimetric analysis of this flare event is presented below.

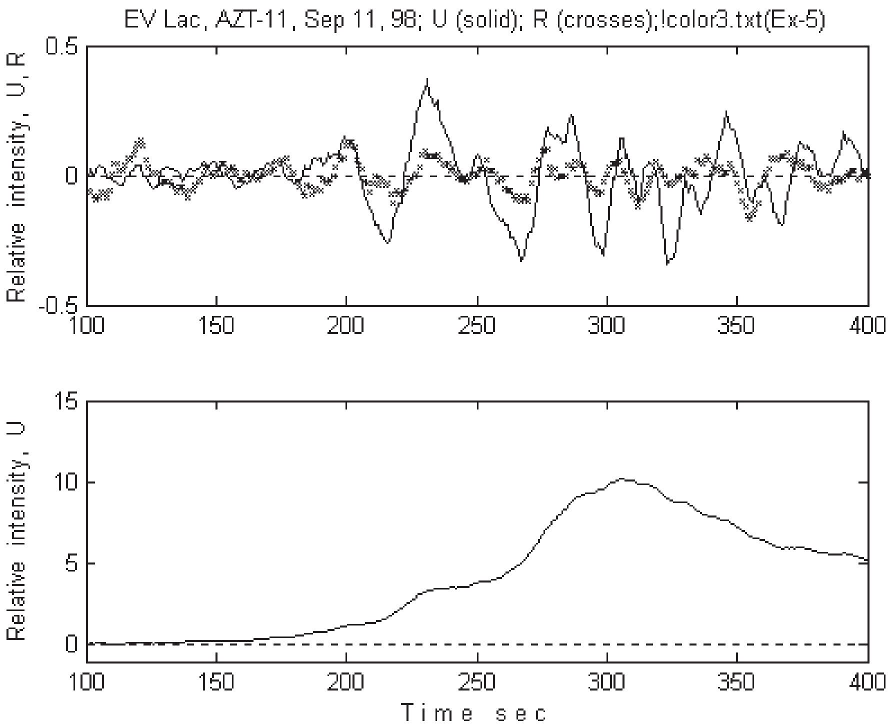

Figure 1. The EV Lac flare light curve in U (lower panel) and superimposed high-frequency oscillations in U (the solid lines) and in R (crosses) bands shown in the upper panel, from the set of data obtained with the 1.25-m Crimean telescope on Sept. 11, 1998, 21:55:02 UT (max). The curve in R is magnified by a factor of 10

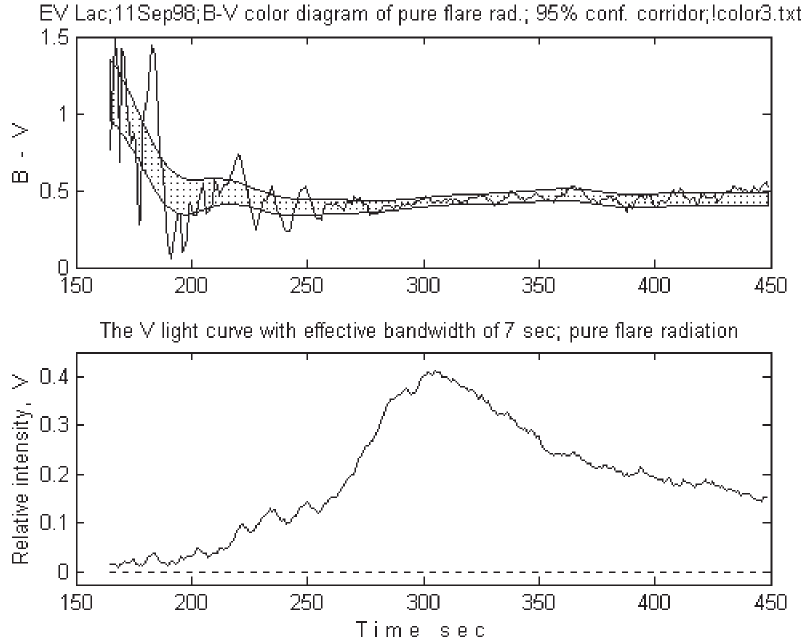

Figure 2. Time variations in the $B-V$ color and the V light curve smoothed by a low-pass filter with an effective bandwidth of 7 s. The error corridor shown presents the 95 % confidence interval for the filtered $B-V$ data from quantum statistics consideration

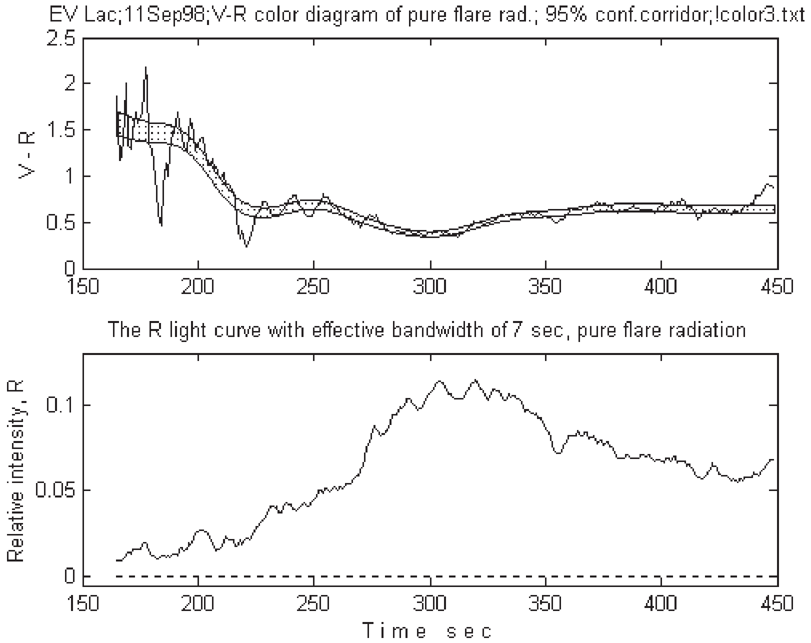

Figure 3. Time variations in the $V-R$ color and the R light curve smoothed by a low-pass filter with an effective bandwidth of 7 s. The error corridor shown presents the 95 % confidence interval

We have used the Kaiser convolution to eliminate the main outburst light curve from the sets of EV Lac data and the moving-average to suppress high-frequency noises. Details of the filtering technique used are described by Zhilyaev *et al.* [6]. The Kaiser filter parameter choices are the cutoff frequency 0.02 Hz, and the width of transition band 0.02 Hz, and the stop band loss 60 decibels. Time variations in the color indices of the $UBVR$ system are shown in Figures 2–3. The error corridor shown presents the 95 % confidence interval for the filtered data. The errors of individual measurements may be estimated from quantum statistics consideration. The filtering procedure decreases the covariance of noises in proportion to the filter pass-band. Rapid variations in colors in the flare rise, many of which vary by a magnitude beyond the error ranges give evidence for their reality.

The analysis in terms of color characteristics may be the basic approach for a full and just evaluation of radiation mechanisms reproducing the flare radiation. Foremost the colors observed have to be good in precision to come to success. We have to note, however, that so far adequate accuracy was achieved only for the most powerful flares near their brightness maximum. Many authors have touched on problems of color-color diagrams to explain where and how optical continuum arises [3, 5]. Theoretical diagnostic diagrams have been calculated for different sources of radiation: for the black bodies of various temperatures, for hydrogen plasma of different optical thickness at the Balmer continuum, for radiation caused by a rapid flow of electrons and protons at an energy of hundreds keV and a few MeV, respectively [2]. Such an approach allowed to conclude that none of mechanism mentioned seems to favor separately in order to account for the observed colors during a stellar flare [3].

We may mention, however, that the color-color diagrams have a diagnostic value with the full awareness of one of mechanism has become predominant in its power. There have not been made successive revisions towards a possible mixture of several mechanisms reproducing the flare radiation simultaneously. What is pertinent in this connection is that the color-color diagrams exclude linear superposition of fluxes because they are logarithmic by nature.

Next we may note that flare events with $\Delta U \leq$ 0.8 mag go out of all classification in the framework of the color-color diagrams because their R, I and partially V fluxes decrease down to undetectable level. We have to note also that some important transient features slip our attention being registered with low time resolution (say, 10 s).

An alternative scheme of color diagnostics that can deepen and widen our understanding of the flare process suggests turning to analysis of the HFO phenomenon. On first sight it culminates near the brightness maximum and dampens at the tile-end of a flare. Using the technique of the 95 % confidence corridor computed by quantum statistics, the color characteristics could be traced with confidence throughout a flare lifetime, including the earliest phase of its development. We shall not here enter into a consideration of the HFO nature because the origin of this phenomenon remains unclear. It is necessary for us to consider what is the role, which HFO play in color dynamics of a flare during its lifetime?

How far limited in its working is the filtering technique in the colorimetric analysis? The limit lies in the fact that noises had assumed quantum nature. At the situation when the 95 % confidence corridor is accepted the technique is working with certainty to the moments when the pure flare radiation measure up levels higher than 0.31, 0.02, 0.013, 0.011 and 0.007 in the $UBVRI$ bands, respectively, with respect to the mean values of quiescent fluxes. We may stress that these levels refer to our particular case of EV Lac as well as the numerical values for the filter used.

RESULTS

Figure 4 shows color-color diagrams with the locations of the theoretical regions computed for various sources of radiation, in particular of hydrogen plasma of different optical thickness at the Balmer continuum [2]. Also shown are color time tracks for the rather smoothed color data and a few widely scattered raw data points falling principally in the earliest phase of a flare lifetime. Typical error ellipses are shown too.

These tracks offer a clear view of which radiation mechanisms can reproduce the flare radiation observed as well as allow an understanding of the role of high-frequency components in the flare process. Time tracks shown in Figure 4 demonstrate that none of the above mentioned mechanism is available on the early stage of the flare. As clearly seen at that interval color indices indicate striking pulsations beyond the error ranges with amplitudes amounting to 0.5 mag and higher. Satisfying agreement between the $B-V$, $U-B$ and $V-R$, $U-B$ data is achieved within about one minute after the flare onset when relative intensities amount to values of about 2.5, 0.24, 0.08, 0.03 and 0.01 in the $UBVRI$ bands, respectively. These values come to only 25 % of the total at the flare maximum. The observed location of all subsequent track points could be reproduced by the mechanism of radiation of hydrogen plasma optically thick at the Balmer continuum with $T_e \simeq 10\,000$ K. It can be seen also that time tracks show subtle systematic runs. This gives confidence that some flare characteristics (temperature, density, optical thickness) tend to evolve slowly through time.

The color-color diagrams in Figure 4 show clearly that HFO lead up to oscillation of the color points. This leads up to grandiose variations in a flare color, from deep red to extremely blue on a time scale of seconds on the ascending phase of the flare. In this context we may deduce that the HFO phenomenon seen in flares plays an important role in theoretical understanding of the flare process. The study of this phenomenon seems to be one of the most powerful tools for physics of stellar flares. What is particularly relevant for us is the ignoring of the HFO phenomenon can lead to the great defect of the modern account of the flare process. There is a good probability that colorimetric analysis in a manner presented here may provide us with a clearer picture of the structure and evolution of stellar flares.

APPENDIX

Both observers and theorists are in the dark about how could appear a stellar flare to the human eye at close range? Figure 5 gives a restored view of flare color behavior as if it would be visible to the naked eye. During this flare on EV Lac on September 11, 1998 stellar light was enhanced by factor of 10 in ultraviolet. To restore the optic characteristics of the flare the $UBVRI$ photometric data were modified according to the spectral sensitivity of the human eye. It is wonder that its primary color exhibits all shades of green. That is because our eye is most sensitive at green wavelengths. It does not perceive ultraviolet all over as well as infrared, and perceives the blue and red lights partially only. On account of high-frequency oscillations the flare shows all the colors of the rainbow, in particular in the flare rise.

[1] *Alekseev I., Antov A., Avgoloupis S., et al.* Coordinated Observations of the Red Dwarf Flare Star EV Lac in 1998 // Kinematics and Physics of Celestial Bodies.–2001.–**17**, N 2.–P. 147–156.

[2] *Chalenko N.* Applications of Theoretical UBVRI Color-Color Diagrams to Colorimetric Analysis of Various Astrophysical Objects // Astron. Rep.–1999.–**43**, N 7.–P. 459–461.

[3] *Gershberg R. E., Shakhovskaya N. I.* Some Results of International Campaigns Initiated by the Crimean Astrophysical Observatory for Invistigation of Flare Stars // Kinematics and Physics of Celestial Bodies, Suppl. Ser.–2000.–N 3.–P. 309–321.

[4] *Rodonó M.* Short-lived Flare Activity of the Hyades Flare Star H II 2411 // Astron. and Astrophys.–1974.–**32**.–P. 337–341.

[5] *Straizys V.* Multicolor Stellar Photometry.–Vilnius: Mokslas Publishers, 1977.

[6] *Zhilyaev B., Romanyuk Ya., Verlyuk I., et al.* Detection of High-frequency Optical Oscillations on the Flare Star EV Lacertae // Astron. and Astrophys.–2000.–**364**.–P. 641–645.

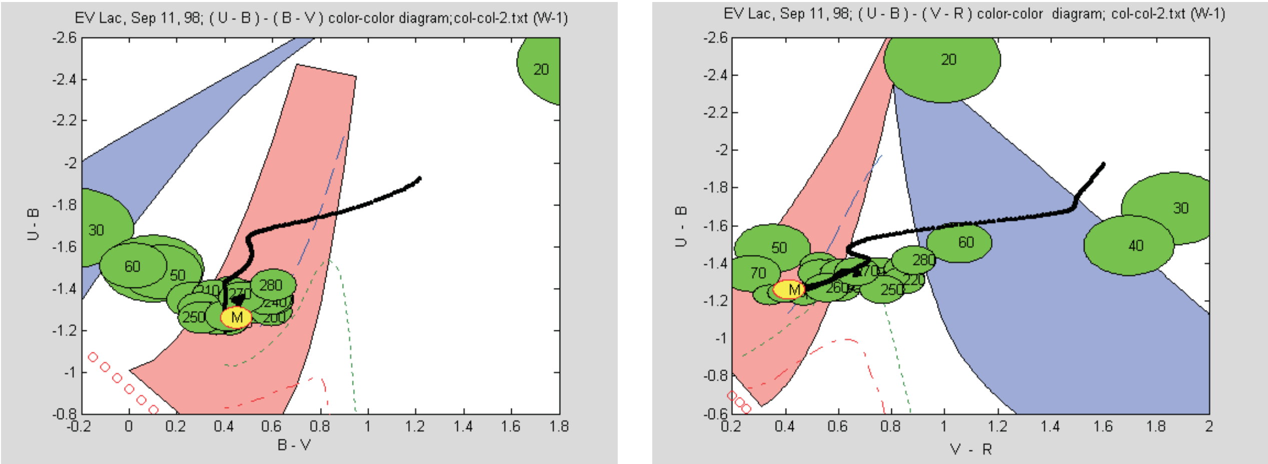

Figure 4. The color-color diagrams of pure flare radiation for the main (the thick line) and raw light curves (the ellipses) smoothed by a low-pass filter with an effective bandwidth of 50 and 3 s, respectively. Theoretical regions for various sources of radiation are shown, namely: radiation of plasma optically thin at the Balmer continuum, with $T_e = 10,000$ K and N_e from 10^{14} to 10^{10} cm^{-3}, the blue area, the same of thick at the Balmer continuum, with T_e from 15 000 to 8 000 K, the pink area. Also shown are the expected radiation of red dwarf upper photosphere heated by a rapid flow of electrons with energies 50, 100, 200 keV (the dashed, dotted, dash-dot lines, respectively) and of blackbody shown as circles [2]. The error ellipses of the respective color indices are marked by run time in seconds from the flare onset. The location of the flare maximum is marked with an M

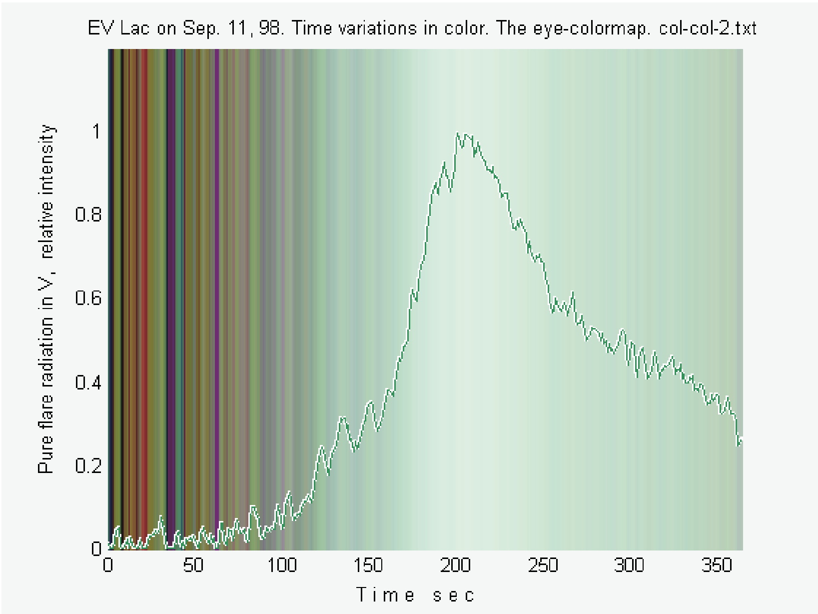

Figure 5. A flare of EV Lac on September 11, 1998. Time variations in color. The eye-colormap