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Fast colorimetry of the flare star EV Lacertae from *UBVRI* observations in 2004

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ABSTRACT

Aims. We report results of a quantitative colorimetric *UBVRI* analysis of two flare events on the red dwarf EV Lac. The photometric data were obtained in September 2004, during the multi-site synchronous monitoring from the four observatories in Ukraine, Russia, Greece, and Bulgaria. These observations confirmed the presence of small-scale high-frequency oscillations (HFO) initially detected by Rodonó (1974, A&A, 32, 337) and recently reconfirmed by the authors. Here we discuss the color characteristics of flares and HFO.
Methods. Colorimetric analysis had been performed with the help of the time tracks in the *UBVRI* color-color diagrams from the earliest phase of flare development. Digital filtering technique was used to evaluate the time-dependent color indices.
Results. As can be clearly seen in the diagrams, color indices oscillate on a time scale of seconds, far exceeding instrumental errors. Regarding the HFO, we conclude that the bulk of a flare oscillates during a major part of its lifetime between the states of hydrogen plasma opaque and transparent in the Balmer continuum. We find that at the peaks of oscillations the color tracks drift into the regions of color-color diagrams corresponding to a blackbody radiation, which provides an estimate of color temperatures from 17 000 to 22 000 K. We also find that flares cover ~1% of the stellar disc.

Key words. stars: flare – stars: individual: EV Lac – stars: activity

1. Introduction

The flaring red dwarfs are the most numerous variable stars, and one of their important features is sporadic flares. They were detected within a whole wavelength range from X-ray to meters in the radio range (Gershberg 2005). Comprehensive observations of these events provide means to study the solar-type activity in stars of different masses and ages. It is known that color indices of red-dwarf flaring stars vary strongly during flares. That in principle allows us to use colorimetric observations for flare diagnostics – see, for example, Kunkel (1970) and Panov et al. (1988). The history of flare colorimetric studies encompasses half a century and was described in detail by Gershberg (2005). Since some photospheric features in stellar spectra remain visible even during strong flares, we suspect that a flare emission is caused by an additional source of radiation on the surface of a star. Therefore, intrinsic emission from a flare can be studied using the difference between output of the star during a flare and a quiescent state.

The most complete colorimetric analysis of stellar flares was carried out in the Crimean Astrophysical Observatory, based on the long-term *UBVRI* observations of EV Lac (Gershberg et al. 1991; Gershberg et al. 1993; Alekseev et al. 1994; Abdul-Aziz et al. 1995; Abranin et al. 1998; Abranin et al. 1998a,b). The full set of theoretical color indices in this photometric system have been calculated previously for a variety of known radiation sources: blackbody for a wide range of temperatures, synchrotron radiation for different spectral indices of relativistic electrons, hydrogen plasma emission for various temperatures, densities and optical thicknesses, and radiation from upper layers of stellar atmospheres heated by different high-energy particle fluxes (Chalenko 1999). Then color indices of flares were estimated for different phases of several strong flares, and these observational indices were compared with the theoretical values on four color-color diagrams in the *UBVRI* system. The comparison showed that none of the considered radiative mechanisms can reproduce observations alone; hence it is necessary to introduce some combination of radiative mechanisms. The best combination turned out to be a short-lived blackbody radiation near flare maxima and long-lived emission of hydrogen plasma with temperatures and densities somewhat higher than in an unperturbed chromosphere (Gershberg 2005).

At the maxima of flares on EV Lac, the blackbody temperature reached $T_{\rm bb} = 10\,000{-}25\,000$ K, and the flare area covered 0.06–1.3 percent of the stellar disk (Alekseev & Gershberg 1997). Note that Mochnacki & Zirin (1980) have approximated optical flare continua at maxima for the red dwarfs YZ CMi and UV Cet by a blackbody radiation $T_{\rm bb} = 7400{-}9500$ K, while Kahler et al. (1982) have used $T_{\rm bb} = 8500$ K to reproduce the YZ CMi flare maximum. Katsova et al. (1991) have used the same approximation with $T_{\rm bb} = 10\,000$ K for another flare on this star. Pettersen et al. (1986), Hawley & Fisher (1992), and Hawley et al. (2003) used $T_{\rm bb} = 9000{-}10\,000$ K to describe the optical continuous radiation of flares on the red dwarf AD Leo; de Jager et al. (1989) have estimated $T_{\rm bb} = 16\,000$ K during the maximum of the very strong flare on UV Cet; Paulson et al. (2006) have found $T_{\rm bb} > 8000$ K for the flare on the Barnard's star.

The cited Crimean results have been obtained from the flare monitoring with a rather low time resolution of about 20 s. The technique of digital filtering recently employed by Zhilyaev et al. (2000) allows the time resolution to improve by 2 orders of magnitude. The first application of the technique resulted in the discovery of HFO in brightness and colors of the detected flares (Zhilyaev et al. 2000, 2003). Similar HFO of stellar flares were confirmed recently by Contadakis et al. (2004). Here we present a complete colorimetric analysis of the two EV Lac flares detected during the multi-site monitoring in September 2004, processed with the digital filtering technique, analyzed with a set of the color-color diagrams, and considered in the network of a time-dependent phenomenological model of flares.

2. Observations

The red dwarf star EV Lac (dM 4.5e) is one of the brightest flare stars. It has the declination of about +44° and therefore can be monitored continuously for up to 8 h during autumn nights. The Synchronous Network of Telescopes, involving telescopes at four observatories in Ukraine, Russia, Greece, and Bulgaria, allows us to study small-scale activity of stars with high time resolution. We observed the flaring star EV Lac from four separate sites over 14 nights in September 2004, using the following instruments: the 2-m Ritchey-Chretien and the 60-cm Cassegrain telescopes at Peak Terskol (North Caucasus) with a high-speed two-channel *UBVR* photometer (Zhilyaev et al. 1992); the 30-inch telescope at Stephanion Observatory in Greece, equipped with a single-channel photometer with digitized readings in the *U*-band (Mavridis et al. 1982); the 1.25-m reflector AZT-11 at the Crimean Astrophysical Observatory with a *UBVRI* photometer-polarimeter (Kalmin & Shakhovskoy 1995); the 2-m Ritchey-Chretien telescope at the Rozhen Observatory and the 60-cm Cassegrain telescope at the Belogradchik Observatory with a single-channel *UBV* photon-counting photometer (Antov & Konstantinova-Antova 1995). The typical integration time was 0.1 s. The sky background was subtracted from all the data. The basic photometric package of the Crimean Astrophysical Observatory was used to transform the instrumental magnitudes to the standard *UBVRI* system. We detected more than a dozen of flare events in *UBVRI* during the monitoring. Here we discuss only two events. These were registered at more than one site using telescopes with the time recording synchronized to better than 0.1 s.

3. Methods

To increase the signal-to-noise ratio we perform digital filtering of the available photometric data. We have used the Kaiser convolution to obtain a low-frequency outburst light curve from the sets of EV Lac data and a moving-average to suppress high-frequency noises (see details in Zhilyaev et al. 2000). Filtering in the frequency domain can be performed by convolving the series' counts $n(i)$ with the filter's pulse response characteristic coefficients $h(i)$:

$$n_f(k) = \sum_{i=-l}^{l} h(i) n(k-i). \tag{1}$$

The filter coefficients are

$$h(k) = h(-k) = \frac{\sin(\pi \nu_{\rm c} k)}{\pi\, k} \cdot \frac{I_0(\eta\sqrt{1-(k/l)^2})}{I_0(\eta)}, \tag{2}$$

where $I(x)$ is the modified Bessel function of the zero's order, η is the parameter that enters the filter's model, and l the number of coefficient pairs of the filter. Three basic input parameters, i.e., (1) the filter's pass band $\nu_{\rm c}$; (2) the width of transition band; and (3) the stop-band loss in the decibel scale, completely determine quantities η, l, and the filter as a whole (for more details see Kaiser & Reed 1977). Thus, using the Kaiser filter we can set limits on signals that would have been aliased through the side lobes into the stop-band frequency domain. The filtering procedure decreases covariance of noises in proportion to the filter's pass band. The errors of individual measurements can be estimated from a quantum-statistical consideration.

4. Results

Below we present the quantitative colorimetric analysis of the two flare events of EV Lac.

The flare on September 14, 2004

Figure 1 shows portions of the outburst light curves of EV Lac (upper panel) and the high-pass filtered light curves of the flares (lower panel) detected during the synchronized observations from three telescopes at the Crimean and at the Terskol observatories on September 14, 2004. The light curves in the *U*-band are not smoothed, but normalized to a unit intensity. There is only a weak indication of HFO in the original photometric data. The lower panel clearly shows the emergence of HFO after an appropriate high-pass digital filtering. The numerical values for the Kaiser filter were: the cutoff frequency $f = 0.167$ Hz, the width of transition band $\Delta f = 0.1$ Hz, and the stop band loss 50 decibels. We also applied a moving-average filter with an effective bandwidth of 1.5 s to reduce noise fluctuations. There is obvious correlation in the records obtained by different instruments at different sites, which lends support to the reality of HFO.

Figure 2 shows the color time tracks of the flare event from September 14, 2004. The flare begins very close to the domain occupied by a blackbody radiation with $T = 17\,000{-}22\,000$ K. The range of temperatures comes from finite covering of the blackbody line by the 95% error ellipse. After 4 s the temperature reaches maximum with $T \sim 18\,500$ K. The flare appears to be opaque only during the maximum brightness (seconds). Then the colors drift to the domain occupied by output from a hydrogen plasma optically thick in the Balmer continuum. The flare's

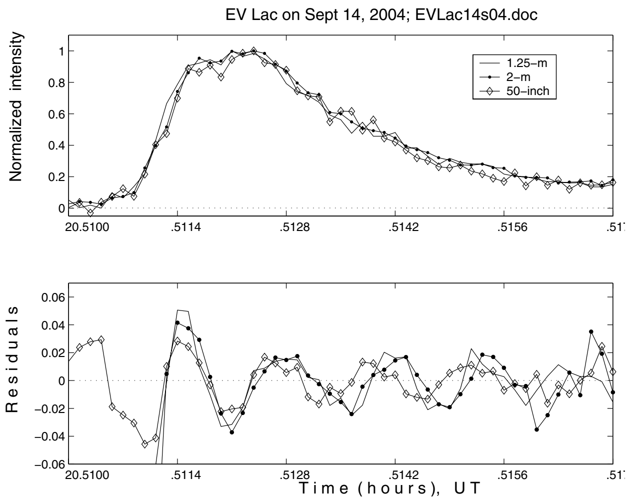

Fig. 1. A flare event in EV Lac, September 14, 2004, 20:31 UT (max), the U-band, based on the multi-site synchronous observations with the Terskol 2-m, Crimean 50-inch, and 1.25-m telescopes (*upper panel*). *The lower panel* shows HFO revealed after the high-pass digital filtering.

temperature may drop down to $T_e \sim 8000$–$10\,000$ K. After that the flare drifts within 4 seconds to the place occupied by radiation of a hydrogen plasma optically thin in the Balmer continuum, with $T_e \sim 10\,000$ K and N_e from 10^{14} to 10^{10} cm^{-3}.

Figure 3 shows the light curves in the U- and I-bands and their least-square polynomial fits. The polynomial fit is considered as representative of the flare's light curve. We analyze the residuals intending to detect any HFO exceeding noise levels. To investigate frequency spectra of the oscillations, the high-frequency residuals in the U- and I-bands were subjected to a power spectrum analysis with the Tukey spectral window (Jenkins & Watts 1969). Power spectra of the residuals in the bottom row of Fig. 3 show low-coherent oscillations in the U and I wavelengths during the outburst, with periods of 4.5 and 6.3 s, respectively. It is likely that only one frequency is strongly excited at a time. Of special note is the clear shift in frequency between the oscillations registered in the U- and I-bands.

The flare on September 12, 2004

Figures 4–8 represent the light curves and color tracks of the second 107 s flare detected on Sept. 12, 2004. All sites in the Ukraine, Russia, Greece, and Bulgaria had registered this flare event. Figure 4 demonstrates the remarkable consistency of the U-band light curves simultaneously obtained by three instruments of the Crimean, Stephanion, and Belogradchik observatories. The smoothed data show clear presence of HFOs in the descending part of the flare. The color-indices and time tracks in the *UBVR* color-color diagrams are based on the data obtained with the Crimean 1.25-m reflector AZT-11. We may see that the $U-B$ and $B-V$ color-indices are opposite in phase (Fig. 6).

Figure 5 shows the power spectra of high-frequency residuals calculated from the data simultaneously obtained by the three remote telescopes. All the spectra give evidence of low-coherent oscillations at 0.06, 012, and 0.16 Hz (periods 17, 8, and 6 s). These harmonics can also be seen in the Bulgarian set, though less clearly due to the smaller aperture of the telescope.

Figure 6 shows both the filtered *UBV* light curves and the color tracks, thus visualizing the long-term trends. The 95% confidence intervals for the color curves were determined under the assumption of a Poisson noise. The points located at the peaks of the light curve and the $B-V$ color index at 12, 29, and 46 s from the beginning of the flare (stars), denotes the passage of the color tracks over the blackbody line shown in Fig. 8. Note that the R and I light curves were excluded from consideration because of intense fluctuations caused by HFO.

Figure 7 shows the color track based on the *UBVR* synchronous data around the flare's maximum. Changes in four spectral ranges also prove that the flare in its maximum is similar to a blackbody source.

Figure 8 shows the color tracks of the flare from September 12, 2004. According to the theoretical color-color diagrams (Chalenko 1999), the flare's onset (and 95% error ellipse) falls in the region corresponding to the radiation of hydrogen plasma optically thick in the Balmer continuum, with $T_e \sim 10\,000$ K. The dashed, solid, and dotted lines situated nearly show an output from photosphere of a red dwarf heated by a rapid flow of electrons with energies 50, 100, and 200 keV, respectively. One may assume that onset of the flare was triggered by an injection of electrons with $E = 100$ keV (the solid line labeled with open triangles).

5. General parameters and colorimetric scenario for the flares of EV Lac on September 12 and 14, 2004

Using color tracks from the *UBVRI* color-color diagrams, we may deduce characteristics of plasma from the earliest phase of the flare's development. As evidenced by colorimetric analysis shown in Figs. 2, 7, and 8, the radiation during the flare's maximum has a blackbody spectrum. The temperature of blackbody radiation may be derived from the color-color diagram. Using the blackbody model for the photosphere of EV Lac in a quiet state, one may estimate the size of flare. The U-band luminosities of the flare and photosphere can be determined from a blackbody spectrum convolved with the U filter response. The area of a flare, s, may be written as

$$\frac{s}{S} = (10^{0.4\Delta U} - 1)\,\frac{F_{U_0}}{F_U}, \tag{3}$$

where S is the area of stellar disk, ΔU is the flare's amplitude in the U-band, and F_{U_0} and F_U are the Planck functions of the quiet star and of the flare with a characteristic temperature T_{bb}:

$$F(T_{bb}) = \int U(\lambda)/\lambda^5[\exp(1.4388/\lambda T_{bb} - 1)]\mathrm{d}\lambda. \tag{4}$$

Here $U(\lambda)$ is the response function for the U-band. We may substitute the latter by a square with a width equal to the FWHM of the actual filter. The observed flare amplitudes in the U-band were 1.47 and 2.10 mag on September 12 and 14, respectively. The color diagrams yield flare colors of $U - B \simeq -1.1$ and $B-V \simeq -0.1$ near the flare's maxima. Hence, the temperature of the flaring layer reaches $\sim$18 500 K. For EV Lac in quiescence one may adopt $T_{\rm eff} = 3300$ K (Pettersen 1980). Then the size of the projected flare area is $\sim$1.1% of the apparent stellar disk for the flare from September 12 and 1.3% for September 14, 2004. These values found are in agreement with ones obtained earlier for 9 strong EV Lac flares with $\Delta U > 1.8$ mag (Alekseev & Gershberg 1997). For flare area coverages of another M dwarf AD Leo Hawley et al. (2003) have found significantly smaller values.

It is very likely that the flare from September 14, 2004 began during a rather short interval of time, about one second, as a small-scale outburst optically thick in the Balmer continuum. In 20 s after the onset, towards the end of the lifetime, the flare

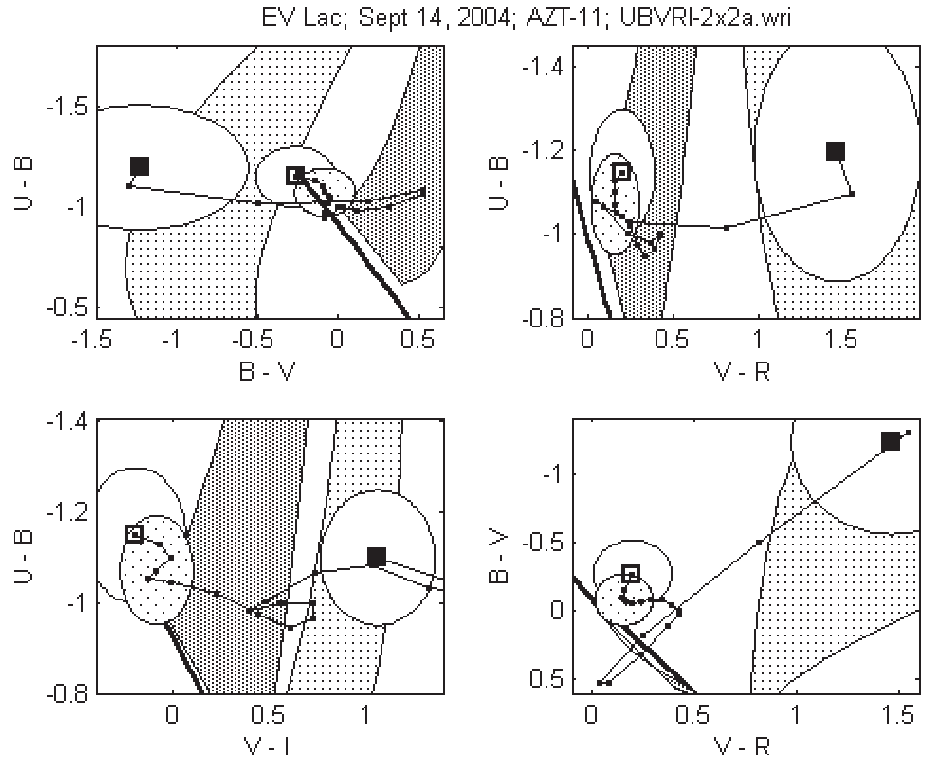

Fig. 2. Color tracks of the flare shown in Fig. 1. This event with amplitude $A_U = 2.1$ mag and lifetime ~20 s was registered at the Crimean 1.25-m reflector AZT-11 on September 14, 2004, 20:31 UT (max). The onset and the end of the flare are marked by open and filled squares, respectively. The 95% error ellipses at the onset, end, and maximum of the flare are also indicated. Markers (filled small squares) retrace the curves with a 1 s time-step. The low point density area denotes color characteristics of plasma optically thin in the Balmer continuum, with $T_e \simeq 15\,000$ K and N_e from 10^{14} to 10^{10} cm^{-3}; the thick point density area covers the region corresponding to plasma optically thick in the Balmer continuum, with T_e from 15 000 to 8000 K. Blackbody radiation follows the heavy line (Chalenko 1999). The blackbody temperature is increasing from below upward.

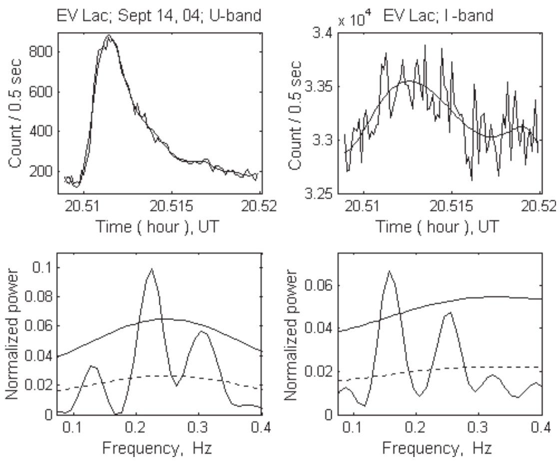

Fig. 3. The light curves of the flare from September 14, 2004 in the *U* (top left) and *I* (top right) filters and their polynomial fits. Power spectra of the residuals (*the bottom row*) show low-coherent oscillations in the *U* and *I* wavelengths during the outburst, with periods of 4.5 and 6.3 s, respectively. The 99% confidence level is marked by solid lines. The lower dashed lines are the mean noise spectra. Practical details in applying spectral analysis are taken from Jenkins & Watts (1969).

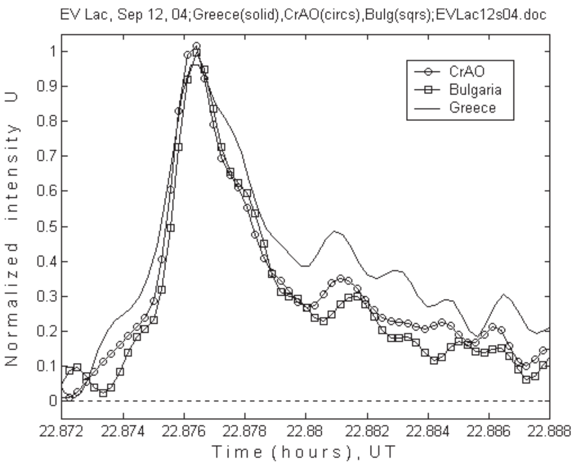

Fig. 4. Multi-site photometry of the flare from September 12, 2004, 22:53 UT (max), as simultaneously seen by the three instruments: Ukraine (circles), Greece (solid), and Bulgaria (squares).

became optically thin, with a temperature ~10 000 K. Figure 1 shows oscillations in the *U* wavelengths with a period ~4.5 s and amplitude of few hundredths of a magnitude.

The color tracks point to the following scenario. Within the initial ~10 s the flare reaches a maximum located in the region occupied by blackbody radiation with $T = 17\,000$–$22\,000$ K. Then the flare starts oscillating between the regions occupied by optically thick and optically thin plasma. At the end of the outburst the color track moves to the region occupied by radiation of hydrogen plasma optically thin in the Balmer continuum with $T_e \sim 10\,000$ K. Some track points marked by thick circles correspond to passages over the blackbody line. These points correspond to the peaks seen in the light curve and the $B - V$ curve at 12, 29, and 46 s (counting from the beginning of the flare and marked by stars, Fig. 6). The $(U - B)$–$(V - R)$ color-color diagram (Fig. 7) proves that the flare in its maximum is similar to a blackbody source of radiation with the most probable value $T_{bb} = 18\,500$ K. The intense, rapid (seconds) fluctuations caused by HFO may change the plasma's opacity, periodically making it optically thin. Therefore, observations with a low time resolution may provide a biased picture of the color changes. One may notice another feature, namely the apparent shift in frequency between oscillations seen in different filters (Fig. 3). We do not have any explanation for this phenomenon.

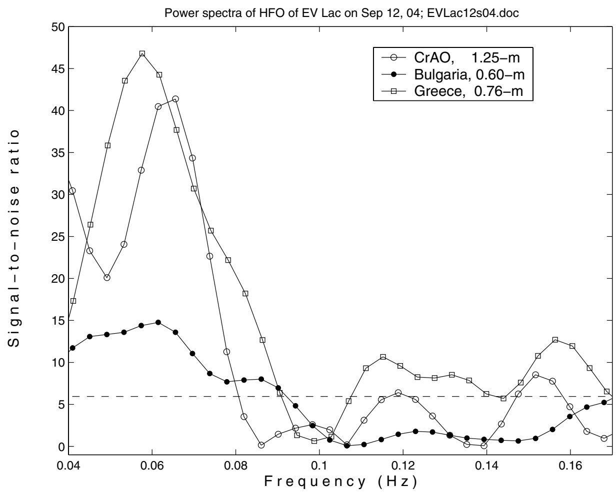

Fig. 5. The power spectra of high-frequency residuals of the flare on EV Lac on September 12, 2004 calculated from the data obtained simultaneously from three sites. The 99% confidence level for white noise data is shown as the dashed horizontal line according to Zhilyaev et al. (2000).

6. Conclusions

The application of new observational technology and new methodology of data processing – a high-speed, multi-site monitoring and digital filtering – provided new results: we confirmed HFO in stellar flares and discovered fast color variations of the flare's radiation. We have shown that such an event is a typical feature of a stellar flare, confirming that the rapid (seconds) HFO clearly exceeds the ranges of instrumental errors. We confirm the general tendency of a flare to shift from a blackbody emission in maximum to a hydrogen plasma emissivity during the decay. Our time-resolved colorimetry clearly demonstrates the non-monotonous character of the drift. The existence of HFO proves that a flare is not a monotonous relaxation process, which follows the primary release of energy, but has some internal structure and non-trivial development.

As is well known, HFOs have been detected in the radio wavelength and X-ray ranges as well. Using the Arecibo radio telescope at 430 and 1415 MHz, Bastian et al. (1990) have studied dynamic spectra of flares in the red dwarf AD Leo and found quasi-periodic pulsations with a characteristic time of about 0.7 s. 100% circular polarization and the brightness temperature near 10^{16} K of the detected radiation evidenced its non-thermal nature, tentatively identified as a cyclotron maser instability operating in an inhomogeneous medium. Similar quasi-periodic pulsations have been detected by Zaitsev et al. (2004) using observations of the UV Cet flare with the Effelsberg radio telescope. In contrast to Bastian et al. (1990), Zaitsev et al. (2004) attributed the effect to the plasma mechanisms – to a combination of MHD and LCR oscillations – and estimated the parameters of the oscillating magnetic loop in the AD Leo stellar corona. With the XMM-Newton mission Mitra-Kraev et al. (2005) have carried out observations of the flare of the red dwarf AT Mic and found a damped oscillation from the flare maximum with a period of around 750 s in the soft X-ray light curve. They concluded that the most likely interpretation of the event is a standing longitudinal slow-mode wave in a flare loop. Therefore, the conclusion on inhomogeneity of the radiation source is correct within the whole wavelength range.

Our first description of the optical HFO in the EV Lac flares (Zhilyaev et al. 2000) was recently interpreted by

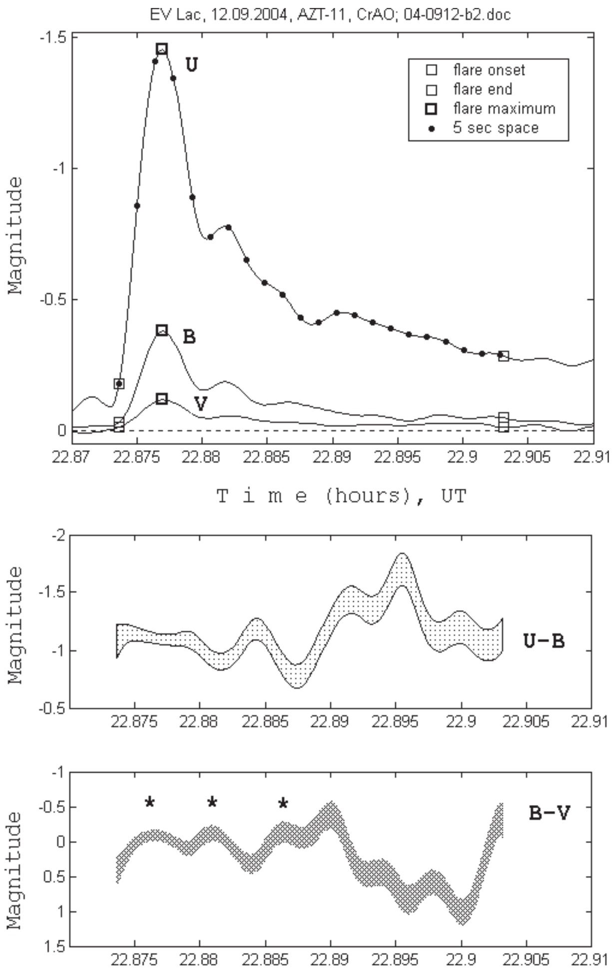

Fig. 6. The filtered *UBV* light curves (*upper panel*) and the corresponding colors (lower panel, with the 95% confidence intervals) visualizing an oscillation with $P \sim 17$ s.

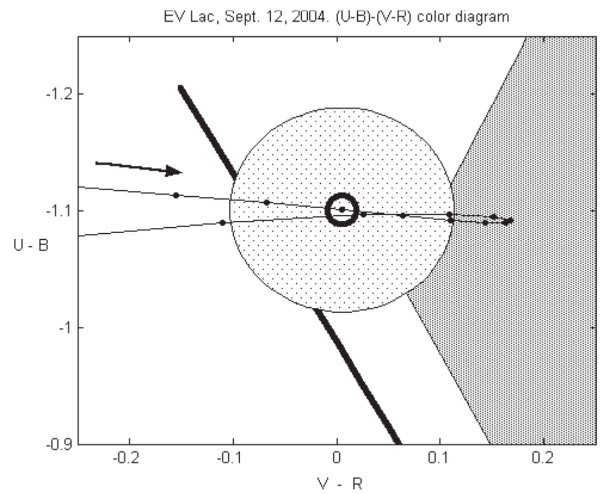

Fig. 7. Color track (with the 95% confidence area) around the flare's maximum. Changes in a flare color $(U-B)-(V-R)$ prove that the flare in its maximum is similar to a blackbody source. The thick line follows blackbody radiation with T_e = 13 000−36 000 K. The 95% confidence interval for temperature at the flare's maximum is 17 000–22 000 K, with the most probable value 18 500 K. Markers (filled circles) retrace the color tracks with 1 s intervals. Note that the $(U-B)-(V-R)$ color-color diagram was calculated only in the restricted domain around the flare's maximum, to avoid the intense fluctuations in the *R*-band caused by HFO.

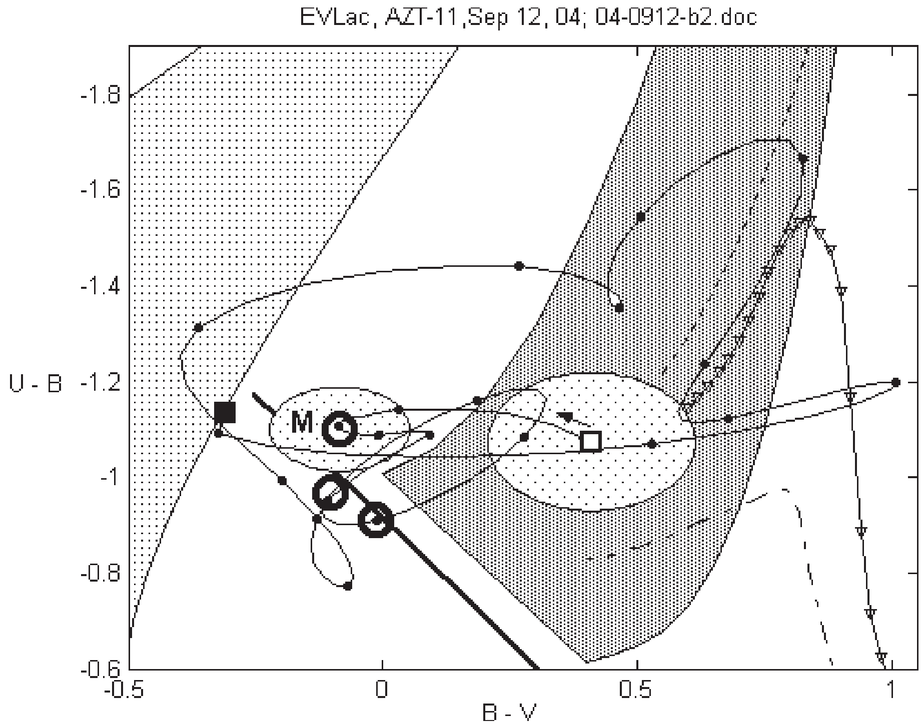

Fig. 8. Color tracks of the flare from Sept. 12, 2004 (duration 107 s), as observed from the Crimean 1.25-m reflector AZT-11 (see also Figs. 4 and 6). The 95% error ellipses are shown at the beginning and at the maximum (letter M) of the flare. The onset and end of the flare are marked by open and filled squares, respectively. Markers (small filled circles) correspond to 5 s intervals. The thick line follows blackbody radiation. The blackbody temperature is increasing from below upward up to 50 000 K. Track points marked by thick circles correspond to passages over the blackbody line.

Kouprianova et al. (2004) and Stepanov et al. (2005). They concluded that a source of such an HFO is located at a magnetic loop footpoint, the pulsations are determined by modulation of the flux of energetic particles descending along a loop with fast magnetoacoustic oscillations. Within the framework of the model, Kouprianova et al. (2004) have estimated its parameters as follows: loop height $\sim 10^{10}$ cm $\sim 0.4\,R_\star$, the plasma density $\sim 2\times10^{11}$ cm^{-3}, the plasma temperature 4×10^{7} K, and magnetic field strength 320 G. Thus, the next necessary step to understand the HFO is to unite the MHD (Kouprianova et al. 2004) and radiative hydrodynamical (Katsova et al. 1997; Allred et al. 2006) approaches. Note, that flare models F10 and F11 calculated by Allred et al. (2006) have durations close to these of the flares detected and described above.

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