COLORIMETRY OF TWO FLARES ON EV LACERTAE FROM UBVRI OBSERVATIONS IN 2004

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ABSTRACT. According to the fast UBVRI photometry data obtained during international synchronous observations of the flaring red dwarf EV Lac, a fine time structure of two flare events is investigated and occurrence of high-frequency oscillations (HFO) during a flare is confirmed. It is revealed that HFO appear at the earliest stages of the flare development. The periods of fluctuations are from several seconds up to tens seconds. Typical amplitudes amount to some hundredths of a magnitude in the U band. HFO lead to significant variations in colors of the pure flare radiation - up to one and more magnitude. The detailed colorimetric analysis allows to note changing of such characteristics of a flare as optical thickness, electron density and temperature during the flare development. In the brightness maximum a flare radiates as a black body with temperature approximately 18500 ± 1500 K. It is established that a flare is oscillating between the states of optically thick and optically thin in the Balmer continuum hydrogen plasma during the most part of its lifetime.

Key words: UBVRI photometry, Stars: flaring: stars: individual: EV Lac.

1. Introduction

Colorimetry is the crucial quantitative method in the analysis of radiation of flaring stars. Multicolor photometry allows to estimate such characteristics of radiating plasma as the effective temperature, electron density, and optical thickness. To estimate these parameters different authors have carried out simulation of color characteristics for various mechanisms of flare radiation. Theoretically, the monitoring of a star in the UBVRI bands during the flare lifetime enables one to receive a detailed picture of changes in flare plasma characteristics with time. However, colorimetry of flaring stars has not yet led to unequivocal conclusions about properties of the pure flare radiation. The main difficulties in interpretation of the colorimetry data are concerned with low time resolution ($5 \ldots 19$ sec) and limited precision of observation in the U band (~ 0.15 mag), whereas variations in color-indexes can amount to one and more magnitude during a few seconds (Zhilyaev et al., 2005).

Last years synchronous observations of flaring stars were carried out with the high time resolution (up to 0.1 sec) with several remote telescopes. The digital filtering technique has been applied to data processing to increase accuracy of brightness and colors estimations of flares. A new fact has been established - occurrence of high-frequency oscillations (HFO) during a flare (Zhilyaev et al., 2000; Zhilyaev et al., 2003). This factor was not investigated in early works on colorimetry. The combination of above approaches allows one to carry out the colorimetric analysis from the very onset of a flare till its fading.

Basic conclusions of the present work are: HFO appear at the earliest stages of the flare development. The periods of oscillations are from several seconds to tens seconds. Typical amplitudes amount to some hundredths of a magnitude in the U band. HFO lead to significant variations in colors of the pure flare radiation - up to one and more magnitude.

It is necessary to note, that recently HFO were found in flaring dwarf stars in the radio (Abada-Simon et al., 1995) and in the x-ray (Mitra-Kraev et al., 2005) too.

2. Observations and results

Observations of the flare star EV Lac were carried out in September, 2004 with the Synchronous Network of Telescopes involving telescopes of four observatories in Ukraine (the 1.25-m AZT-11 and 50", CrAO), Russia (the Peak Terskol 2-m), Greece (the Stephanion 76-cm) and Bulgaria (the Rozhen 2-m, and the Belogradchik 60-cm). For 14 nights of observations more than ten flares have been registered.

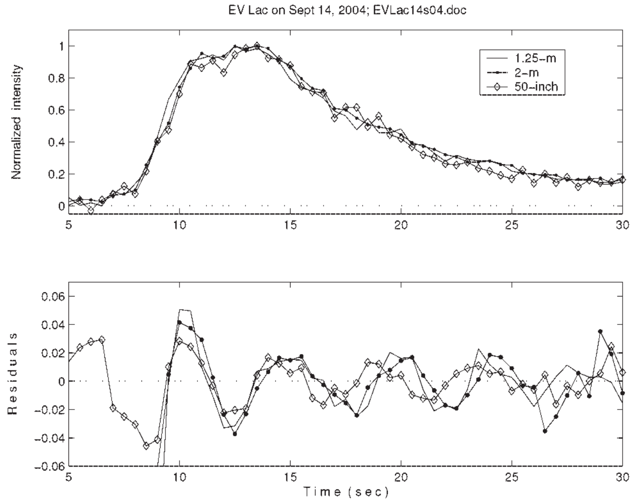

Figure 1: A flare event on EV Lac, September 14, 2004, 20:31 UT (max). See text.

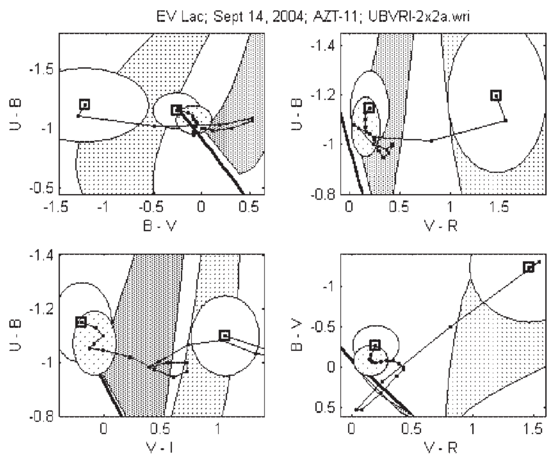

Figure 2: Color time tracks of the flare in EV Lac, September, 14th 2004.

In the present work we analyze two flares observed simultaneously on three telescopes synchronized up to 0.1 sec in UTC. A flare of EV Lac on September 14, 2004 (maximum at 20:31 UT) was observed with three telescopes: the 2-m (Terskol), the 50" and AZT-11 (CrAO). The amplitude of a flare in the U band amounts to two magnitudes, duration about 40 sec.

Fig 1 shows fragments of light curves of the flare in the U band both before (top) and after (bottom) the high-frequency filtering. The light curves are normalized to unit intensity in a brightness maximum. One can see only weak signs of HFO in the raw photometric data. The bottom graph shows clearly a presence of HFO after corresponding high-frequency digital filtering of the light curves. The period of fluctuations is 4.5 sec, amplitude - a few hundredths of a magnitude. Obvious correlation in the data received simultaneously on remote telescopes evidences the reality of HFO. Presence of HFO is revealed in other spectral bands too. The power spectra of residuals obtained with the telescope AZT-11 in the U and I bands show low-coherent oscillations with periods of 4.5 and 6.3 sec, respectively. There is a clear shift in frequency between the oscillations registered in the U and I bands.

The UBVRI photometry data (AZT-11, CrAO) allow us to trace time variations of color-indices and to develop the time color tracks technique for flare plasma diagnostics and estimating its thermodynamic characteristics. The interval of time suitable for colorimetric analysis was limited to 20 sec because of low amplitude of a flare in the R and I bands, though the flare remained visible in the U band during some more 40 sec. Variations detected in color-indices during a short-term period of the flare lifetime amount to one magnitude and more.

Figure 2 shows time evolution of color-indices of the pure flare radiation. The beginning and the end of a flare are marked by squares. The 95% error ellipses in the beginning of a flare (b), in the maximum and in the end of a flare (c) are shown too. Markers on tracks follow with a time step of 1 sec.

To prepare the color-color diagrams the results of color-indices calculations for various sources of radiation were used (Straizys, 1977; Chalenko, 1999). The light gray area denotes the color characteristics of hydrogen plasma optically thin in the Balmer continuum with T_e = 10000 K and N_e from 10^{14} to 10^{10} cm^{-3}, the deep gray area corresponds to optically thick plasma with T_e from 15000 to 8000 K. The heavy black line notes the blackbody radiation. The flare beginning is close to the area occupied by radiation of a blackbody with T from 17000 to 22000 K. For 4 sec a flare reaches its maximum at temperature T_{bb} = 18500 K. Plasma of a flare appears opaque only near to a maximum of its brightness within several seconds. Then the tracks run to the area of hydrogen plasma optically thick in the Balmer continuum. The temperature of a flare drops to T_e = 8000 - 10000 K, and for some seconds a flare passes in the area occupied by hydrogen plasma optically thin in the Balmer continuum with T_e = 10000 K and N_e from 10^{14} to 10^{10} cm^{-3}.

All the sites in Ukraine, Russia, Greece and Bulgaria had registered the second flare event on September 12, 2004. The amplitude of a flare was about 1.5 magnitudes in the U-band, duration was about 150 sec.

Both the initial and smoothed data clearly show the presence of HFO on a descending part of a flare. The power spectra calculated from these light curves detect oscillations with periods about 17, 8 and 6 sec.

Figure 3 represents the light curves of a flare observed with 3 telescopes in CrAO, Bulgaria and Greece and high-frequency oscillations in brightness in the U band after elimination of the main flare light curves. These graphs reveal that HFO arise just before a flare,

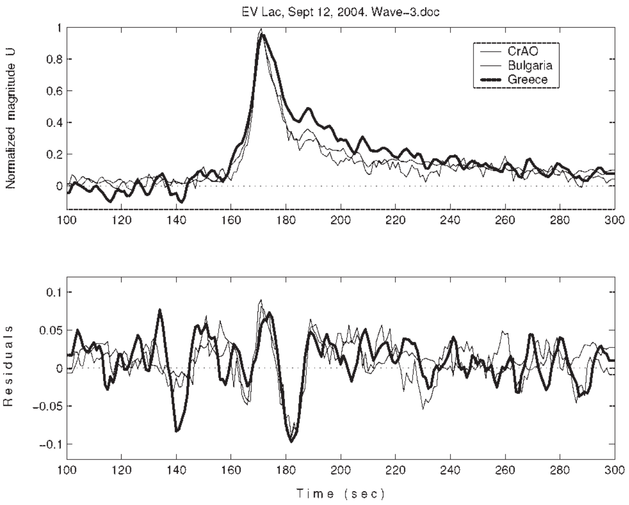

Figure 3: The light curves of a flare on EV Lac, September 12, 2004, observed with 3 telescopes in CrAO, Bulgaria and Greece. See text.

maybe provokes a flare; it lasts about one minute, its period is about 17 sec. The low-frequency UBV light curves and color-indices of the pure flare radiation show evidently oscillations with a period about of 17 sec (Figure 4).

The light curves in the R and I bands have been excluded from consideration because of intensive variations caused by HFO. On the (B-V) curve asterisks note peaks at the moments 12, 29, 46 sec from the accepted flare's onset. As we shall see below, in these points the track of a flare on the color-color diagram crosses the blackbody line.

Figure 5 represents a color time track of this flare. Markers on the track follow with a time step of 5 sec. According to the theoretical color-color diagrams (Chalenko, 1999), the flare's onset falls in the area corresponding to the radiation of hydrogen plasma optically thick in the Balmer continuum with $T_e \sim 10000$ K. In the same area the radiation of the photosphere heated by a rapid flow of electrons with energies 50, 100 and 200 keV is localized (the dashed, solid and dotted lines). During approximately 10 sec from the accepted onset the flare reaches a maximum and radiates as a blackbody with T_{bb} = 17000 - 22000 K with the most probable value of 18500 K. Then the flare starts oscillating between the areas of the diagram occupied by hydrogen plasma optically thick and optically thin in the Balmer continuum. At the end of a flare (marked by a square) the track moves towards the area of radiation of optically thin hydrogen plasma with $T_e \sim 10000$ K.

Thick black circles correspond to peaks on the (B-V) color curve (see Fig 4) and fall to points where the flare track crosses the blackbody line. For the limited segment in the vicinity of a flare maximum

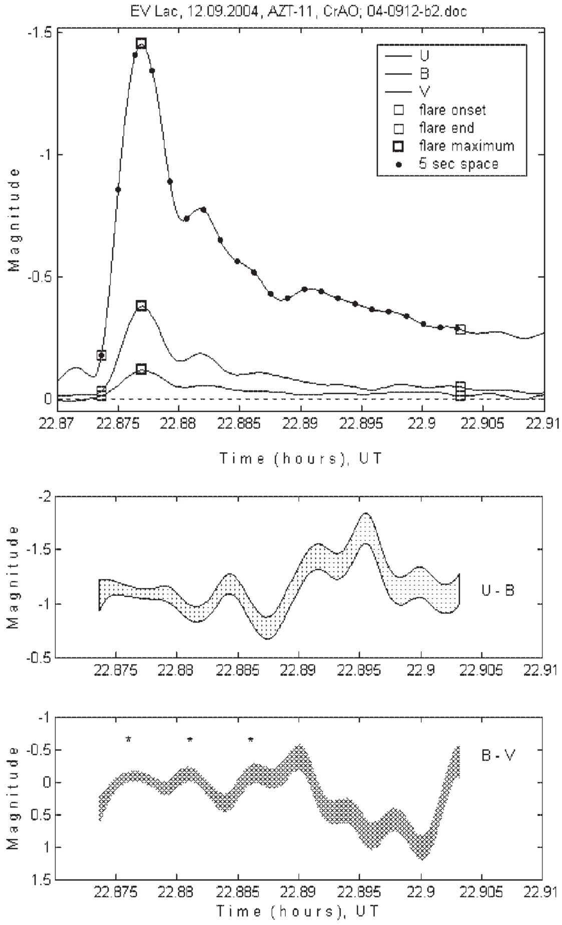

Figure 4: Low-frequency UBV light curves and the corresponding colors of the flare in EV Lac, September, 12th 2004.

it is possible to estimate the (V-R) color-indices too. The color-color diagram (U-B) - (V-R) confirms that a flare in its maximum radiates as a blackbody with temperature $\sim$ 18500 K.

3. Conclusion

The detailed colorimetric analysis of two flares on EV Lac has allowed to notice changes in optical thickness and electronic density during the development of a flare and to estimate temperature in the flare maximum. A new unknown earlier fact has been established: oscillations of plasma of a flare between the states of optically thick and optically thin in the Balmer continuum.

These oscillations have recently found a theoretical explanation (Kouprianova et al., 2004; Stepanov et al., 2005). HFO are connected with fast magnetoacoustic oscillations of magnetic coronal loops on a star. The theory enables to estimate the main parameters of the coronal loops (temperature, electron density and the typical sizes). This opens new prospects for studying

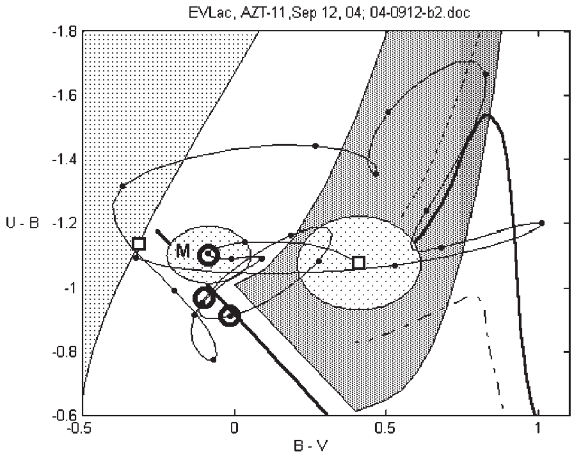

Figure 5: Color tracks of the flare from September, 12th 2004. Markers correspond to 5-s intervals. The beginning and the end of the flare are marked by squares. 95% error ellipses are shown at the beginning and at the maximum of the flare. Thick circles correspond to maxima on color curve B-V (asterisks in Figure 4). It is interesting, that in these points the track crosses the blackbody line.

the coronas of flaring stars, specific *"coronal seismology"*. The synchronous observations of flaring stars in the UBVRI-system with several remote telescopes with high time resolution may be a source of such a work.

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