Astron. Astrophys. 364, 641–645 (2000)

ASTRONOMY AND ASTROPHYSICS

Detection of high-frequency optical oscillations on the flare star EV Lacertae

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Received 10 May 2000 / Accepted 19 October 2000

Abstract. Many-site multichannel simultaneous observations of the flare star EV Lac revealed high-frequency brightness oscillations superimposed on the mean flare light curve. Oscillations occur at the earliest stage of a flare and are visible during the high state. Coherent oscillations of 26 and 13 sec were seen during three flare events. The pulsed fractions were 2.5% in the B band and 10–15% in the U band. This oscillatory phenomenon can be used to improve our understanding of the flare process.

Key words: stars: flare – stars: oscillations – stars: individual: EV Lac

1. Introduction

The first quantitative characteristics of optical flares of the UV Ceti-type red dwarf variables consisted of estimations of their amplitude and duration. Subsequent photoelectric monitoring gave more detailed data on the whole light curve for such events. However, attempts to represent these more complete light curves within the framework of different physical and formal mathematical models did not lead to any understanding of the events which caused them (Gershberg 1970; Coluzzi et al. 1978). Investigators have examined the following characteristic features of light curves of stellar flares: fast brightness decays just after flare maxima (Shakhovskaya 1974), preflare dips in stellar brightness (Cristaldi et al. 1980), the second maximum of flare brightness (Katsova & Livshits 1992). It should be noted that when analyzing the solar flares, one can distinguish beginning impulse phases and subsequent thermal gradual phases of flares. Amongst the vast variety of stellar flare light curves, a special place is occupied by the flare in the Hyades flare star HII 2411, which occured on the 20th November 1972 and was detected by Rodonó (1974). During this rather intense flare, he registered highly oscillatory phenomena with the oscillation period varying from 13.7 to 12.4 s throughout the recording time of about 12 min; the oscillation amplitude appeared to be constant and was equal to about 25% of the mean intensity in the quiescent phase in white light. As was noted by Rodonó, the observed rapid oscillations were not visible during the out-of-flare phases or during the development of other, smaller flares. For the next quarter of a century, no further similar events were observed. Here, for the first time, we describe similar optical brightness pulsations in the EV Lac flares which we detected with a more accurate technique including many-site multichannel monitoring and which we analyzed with much more sophisticated methods.

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2. Observations

The detection of intrinsic small-scale light fluctuations in stars is hampered by atmospheric disturbances and instrumental imperfections. These limitations present an often insuperable barrier to observers operating with a single telescope. Such difficulties, however, may be overcome by the simultaneous use of several telescopes. The key idea contributed by the synchronous network of optical telescopes is as follows: operations of distant telescopes are synchronized to UTC time within the sampling time; consequently, the different datasets can be considered as sets with the same valid signal and uncorrelated atmospheric and photon noises. In this case, using available statistical procedures for simultaneous photometer readings, it is possible to identify instrument faults, to increase the signal-to-noise ratio and to detect signals that may be comparable to that contributed by intrinsic noise sources.

The observational data for the flare star EV Lac reported here were obtained from four separate sites over 19 nights in September–October 1998. The instruments which were used were the following:

- the 2 m Ritchey-Chretien and the 60-cm Cassegrain telescopes at Peak Terskol (North Caucasus, 3100 m a.s.l.) 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 B band (Mavridis et al. 1982);
- the 1.25 m reflector AZT-11 at the Crimean Observatory with a UBVRI photometer-polarimeter (Kalmin & Shakhovskoy 1995);
- 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. For low amplitude flare events the readings were rebinned to 0.6, 1.0 or 1.2 s. The sky background was subtracted from all the data presented here. The UB data were converted to a relative intensity scale with respect to the mean values of quiescent fluxes.

More than a dozen flare events were observed on EV Lac in UBVRI during the observation period. Three events were selected for the present paper. Two of these were registered at more than one site using distant telescopes operating synchronously to an accuracy of 0.1 s.

3. Methods and results

To detect small oscillations, large intrinsic intensity variations must first be removed. To achieve this, we apply high-pass filtering. This may be realized by subtraction of low-frequency components from the time series. After that, the residuals are devided by the mean quiescent intensity to obtain only the high-frequency fractional intensity variations.

Frequency filtering can be performed by convolving the series counts $n(i)$ with the filter pulse response characteristic coefficients $h(i)$:

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

The spectra of the filtered and initial series $G(f)$ and $S(f)$ are related by the expression

$$G(f) = S(f) \cdot H(f). \quad (2)$$

The frequency and pulse response characteristics $H(f)$ and $h(i)$ are related by the reciprocal Fourier transformation

$$H(\nu) = h(0) + 2\sum_{k=1}^{l} h(k)cos(\pi\nu k), \quad (3)$$

where the frequency $\nu = f/f_N$ is given in units of the Nyquist limiting frequency $f_N = 1/(2\Delta t)$ and Δt is the sampling time.

The ideal low-frequency filter with a cutoff frequency $\nu_c < 1$ with the frequency and pulse characteristics

$$H(\nu) = \begin{cases} 1, & \nu \le \nu_c \\ 0, & \nu > \nu_c \end{cases} \quad (4)$$

$$h(k) = \frac{\sin(\pi\nu_c k)}{\pi\, k} \quad (5)$$

cannot be practically realized, as the number of the terms l must be infinite in order for the condition (4) to be fulfilled.

The simplest low-frequency filter is the moving-average one. The pulse coefficients of this filter are constant: $h(i) = 1/L$, where $L = 2l+1$ is the filter length. The frequency characteristic of the filter is

$$H(\nu) = \frac{1}{2l+1} \cdot \frac{\sin(2\pi(l+1/2)\nu)}{\sin(\pi\nu)}. \quad (6)$$

The filter passband is $\nu_c = 1/(2l+1)$. However, this filter has many disadvantages, among which is the aliasing effect, whereby some fraction of the signal power may percolate through the filter side lobes. This difficulty is easily resolved by the use of the more refined near-ideal Kaiser filter (Rabiner & Gold 1975). The filter coefficients are

$$h(k) = h(-k) = \frac{\sin(\pi\nu_c k)}{\pi\, k} \cdot \frac{I_0(\eta\sqrt{1-(k/l)^2})}{I_0(\eta)}, \quad (7)$$

where $I(x)$ is the modified Bessel function of the zero order, η the parameter that enters the filter model, l the number of filter coefficient pairs. Three basic input parameters, i. e. (1) the filter passband ν_c, (2) the width of transition band and (3) the stopband 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 side lobes into the stopband frequency domain.

We have used both the moving-average and Kaiser convolutions to eliminate the main outburst light curve from the sets of EV Lac data. In our cases mentioned below, the cutoff frequency values of 0.067, 0.055, and 0.033 Hz were employed. This removes any variations in time scales greater than 15, 18 and 30 s, respectively. From comparison studies of the moving-average and Kaiser convolutions, it has been found that the oscillation pattern does not change, disregarding minor variations occurring in the vicinity of sharply defined changes in the light curve.

Fig. 1b shows a portion of the high-pass filtered flare light curve of EV Lac, obtained at Peak Terskol with the 2 m telescope. Readings in the U band were taken every 0.2 s. Well-defined short-period oscillations are superimposed on to the very intense main flare plotted in Fig. 1a. The gap in the plot in Fig. 1b is due to the transition process resulting from filtering in the vicinity of the sharp flare maximum in that case.

The numerical values for the Kaiser filter were: the cutoff $f_c = 0.067$ Hz, the width of transition band $\Delta f_t = 0.032$ Hz, the stopband loss is 60 decibels and the time span of the filter is 35 s.

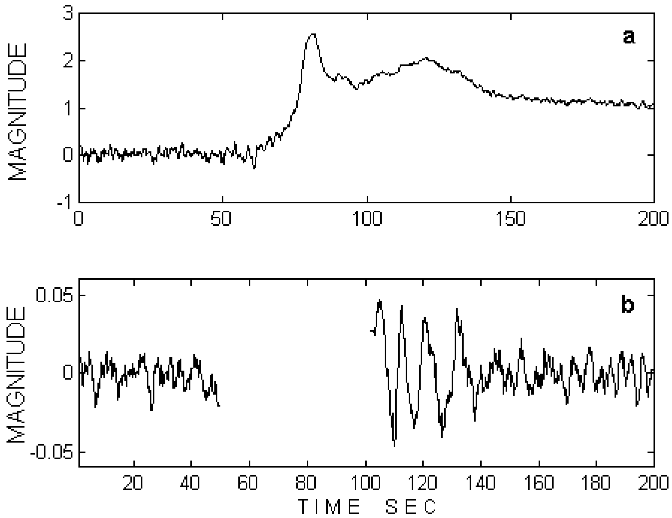

Fig. 1a and b. The EV Lac outburst light curve (upper panel) and superimposed high-frequency oscillations (lower panel), as seen by the 2 m telescope at Peak Terskol on October 8, 1998, 18:03:01 UT (max), U-band.

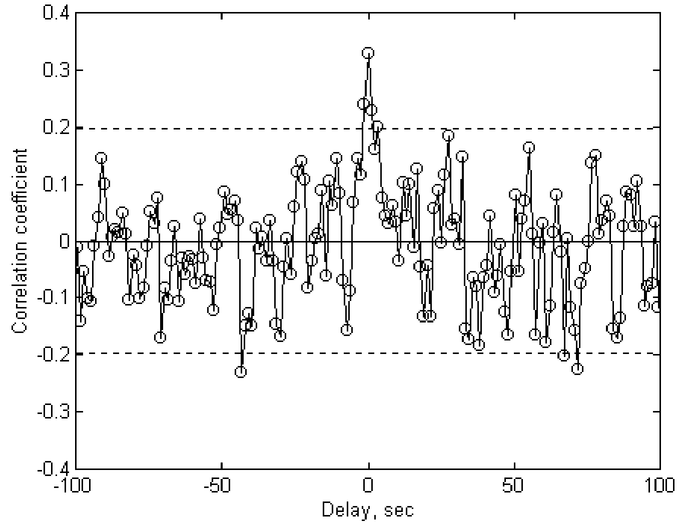

Fig. 3. The cross-correlation between the sets of high-frequency oscillation data shown in Fig. 2a. The dashed lines show the 99% confidence level for the sample correlation coefficient of two mutually independent normal variables.

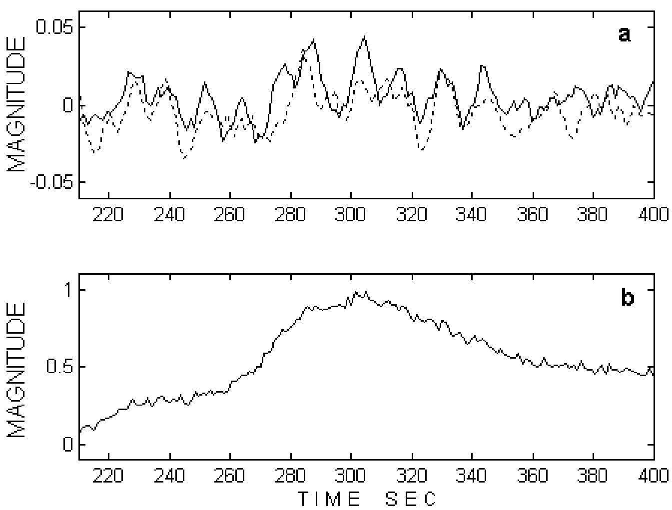

Fig. 2a and b. Portions of the high-frequency B-band remains (upper panel) and of the main light curve (lower panel) from the sets of EV Lac data obtained with the Crimean (solid line) and Greek (dotted line) telescopes on September 11, 1998, 21:55:02 UT (max).

The flare event in Fig. 1 is a clear example of an extreme strong excitation of the HFO with a sudden onset and a decay similarly to that of HII 2411 reported by Rodonó.

The above inferences about high-frequency oscillations were tested by means of the results of many-site synchronous observations. Fig. 2a shows the simultaneous observations of the oscillations on EV Lac at the Crimean and at the Stephanion observatories. Fig. 2b shows the main flare curve in B band with sampling time of 1.2 s. Time variations in oscillations were detected by subtraction of a moving average over 15 points (18 sec) and normalized to the quiescent intensity as was mentioned above. A comparison between these two measurements obtained from synchronous observations at different sites showed obvious correlations significant at greater than 99% confidence level (Fig. 3). A period of 12.8 $\pm$ 0.7 s (0.078 Hz) was obtained from the times of maxima plotted in Fig. 2a and a mean amplitude of 0.025 mag was calculated. From these facts we can be assured that both an atmospheric and an instrumental origin for the high-frequency oscillations can be ruled out with a high degree of confidence.

During our observations, multicolor monitoring of EV Lac was being carried out constantly only in Crimea. But in some cases, flare events were registered simultaneously in different bands from different sites. From the many-site observations, there is experimental evidence that oscillations occur around the flare maximum phase in B color (Fig. 2). Now we have a good chance of following its characteristics, including color variations, during the whole flare light curve.

Fig. 4 gives some insight into the way in which high-frequency oscillations arise and develop during the progress of a flare. An illustrative example of a strong excitation of oscillations is furnished by Fig. 4a. These oscillations first arise at the earliest stage of the flare development, with a frequency of 0.039 Hz (the period = 25.7 $\pm$ 1.8 s). Some time later they transform into a wave of a twofold frequency. Their amplitude may reach 10 % of the quiescent intensity in the U band and about five times lower in the B. A further example of a highly-blue oscillation color is given in Fig. 5. This figure shows the oscillations obtained at the Belogradchik (U-band) and Stephanion (B-band) observatories synchronously. The high-frequency B-band residuals magnified by a factor of six practically coincide with the U ones. At the same time the expected dU/dB ratio between U and B fluxes, caused by the atmospheric scintillation, lies in the range from 1 to 1.2, depending on the aperture of the telescope (Stecklum 1985). The result lends additional support to the reality of the high-frequency oscillations.

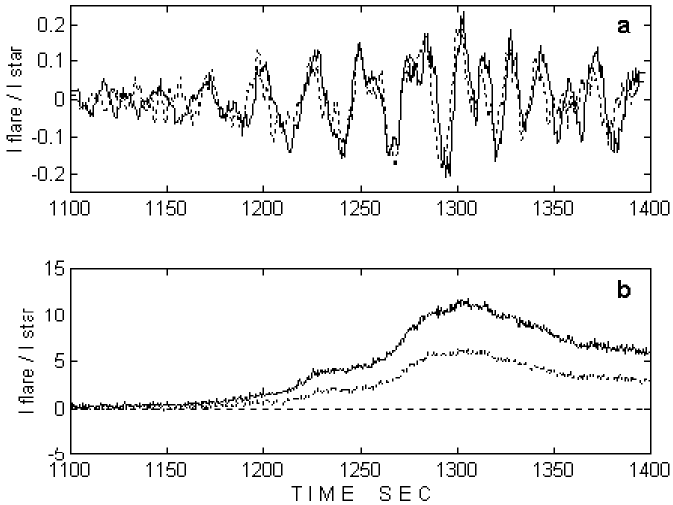

Fig. 4a and b. Time variations in high-frequency oscillations in the U (solid) and B (dotted) bands from the sets of EV Lac data obtained at Crimea on September 11, 1998, 21:55:02 UT (max), (upper panel). The lower panel represents the raw main U and B light curves. Both B curves are magnified by a factor of 5.

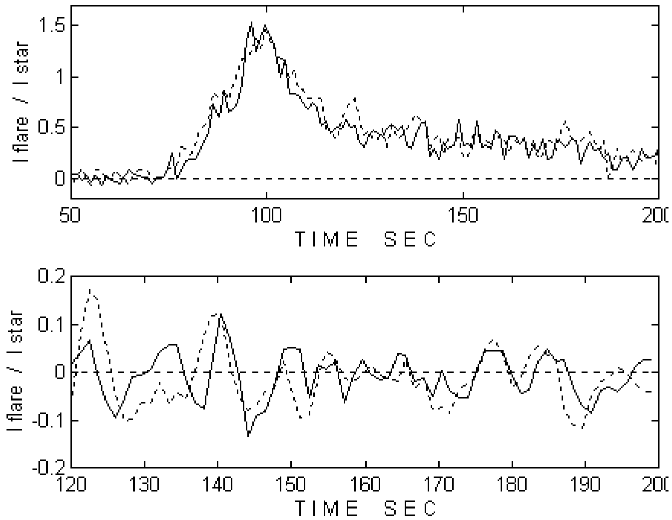

Fig. 5. The magnified B-band and raw U-band light curves of the EV Lac flare on September 15, 1998, 22:30:26 UT (max) (upper panel) as seen simultaneously by the Stephanion 30 inch telescope (dotted line) and the Belogradchik 60 cm telescope (solid line). The lower panel shows time variations in high-frequency oscillations; both curves are strongly correlated at a more than 99% confidence level.

To investigate the oscillation frequency spectra, the high-frequency residuals of the outburst light curve in the U band were subjected to a power spectrum analysis with the Tukey spectral window, as described by Jenkins & Watts (1969). The power spectral density $P(f)$ may be computed as the Fourier transform of the apodizated autocovariance function $c(k)$

$$P(f) = \delta t \left| \sum_{k=-(L-1)}^{L-1} w(k) \cdot c(k) e^{-i2\pi f k \Delta t} \right|. \tag{8}$$

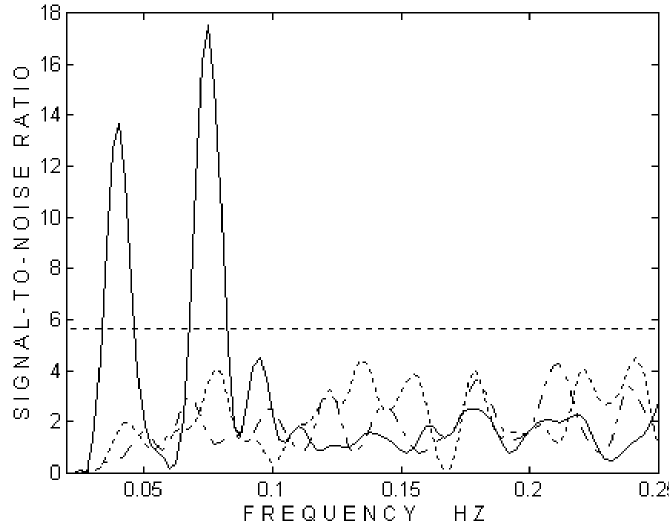

Fig. 6. Power spectra of high-frequency oscillations calculated from three sets of data shown in Fig. 4, transformed into a signal-to-noise ratio scale. The solid line indicates an early rise and decline region of the outburst. The dashed and dotted lines correspond to a preflare and flare tail regions, respectively. The 99% confidence level for white noise data is shown as the dashed horizontal line.

$$c(\tau) = \langle n(t) n(t+\tau) \rangle - \langle n(t) \rangle^2, \tag{9}$$

$n(t)$ is the number of photons detected during the sample time Δt, $\tau = k\Delta t$, $k = 0, \pm 1, 2, 3, \ldots$. We use the Tukey window

$$w(k) = \begin{cases} \frac{1}{2}(1 + \cos \frac{\pi k}{L}), & |k| \le L \\ 0, & |k| > L \end{cases} \tag{10}$$

where $L < N$ is a cut off portion of the total number of measurements N that allows adjustment of the spectral resolution.

Two kinds of noise are typical for time-series photometry of stars: scintillation noise from the atmosphere and stochastic Poisson noise due to the limited number of photons detected, with the uniform spectral density. If the latter prevails (which is common with faint stars, such as EV Lac), the signal-to-noise ratio $Q(f)$ is proportional to the power

$$Q(f) = \frac{P(f)}{\sigma^2} \cdot 2L \tag{11}$$

where σ^2 is the variance of the count rate $n(t)$. In this case the noise peaks in the spectrum are described by the χ^2_ν statistic

$$Q(f) = \frac{2}{\nu} \chi^2_\nu \tag{12}$$

For the Tukey window we have the degree of freedom $\nu = 2.67 \cdot N/L$ and a spectral resolution $1.33/(L\Delta t)$ at half-maximum of the spectral peak. From Eq. (12) we establish a threshold for detecting a signal at the confidence level β

$$Q \ge \frac{2}{\nu} \chi^2_{\nu, 1-\beta} \tag{13}$$

The power spectra in Fig. 6 indicate clearly that an oscillation feature occurs during the outburst phase. This oscillation feature is absent both in the preflare state and at the late flare tail. Two harmonics were detected at 0.039 and 0.078 Hz, both during the early rise and the early decline phase of the outburst. The remarkable fact is that EV Lac also exhibits the short-period harmonic at 13 s, as in the case of HII 2411 reported by Rodonó (1974).

4. Conclusions

Due to many-site multicolor synchronous monitoring of the flare star EV Lac and the careful treatment of the data obtained, we have confirmed the reality of rapid optical brightness oscillations during a significant part of a flare lifetime, as was discovered by Rodonó (1974).

Our findings, based on three flare events in EV Lac, allow us to conclude that high frequency optical oscillations are coherent, with periods of 13 and 26 s and amplitudes of 0.025 mag in the B band and larger by a factor of 5 in the U band. These findings raise a question: what oscillate in a flare?

It is known that such oscillations of a quasi-period of 5–10 s were detected at 1.4 GHz in the very active dMe flare star AD Leonis in a dozen bursts with the 305 m diameter Arecibo radio telescope (Abada-Simon et al. 1995). A closeness of the frequencies mentioned suggests a physical connection; however, it is clear that radio and optical emissions cannot originate from the same region. Therefore, one should think only about heterogeneous dynamical structures. Such structures – closed magnetic loops – are already considered for X-ray flare models in red dwarf stars – see for instance Reale et al. (1997).

For an oscillation period of 20 s and the Alfven velocity for $n_e \sim 10^{13} cm^{-3}$ (Baranovsky et al. 2000) and $B \sim 300$ G, an oscillating body's size is $l \sim 4 \cdot 10^8 cm$. According to Alekseev & Gershberg (1997), a typical area of an EV Lac flare with an amplitude $\Delta\ U \sim 1 - -2$ mag is several units of $10^{18} cm^2$. Only 1 or 2 loops with estimated l can be located on such area. In such a case, one can observe coherent oscillations. This should be regarded as an argument in favour of selfconsistence in our scheme. However, the cause of oscillations remains unknown.

Acknowledgements. We would like to thank Prof. R.E. Gershberg and Prof. J.H. Seiradakis for productive discussions.

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