Starquakes on the red dwarf EV Lac .

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EV lac has been subjected of extending research for many decades at the Stefanion Observatory. Apart of the spectacular flaring phenomena, the results of the analysis of the one colour (B) observations of the Stefanion Observatory at any stage of their activity (quiescence, weak flares, strong flares),indicate that: (1) Transient high frequency oscillations occur during the flare event and during the quiet-star phase as well; (2) The Observed frequencies range between 0.0005Hz (period 33min) and 0.3 Hz (period 3s) not rigorously bounded.. It is interesting that transient oscillations appear also far apart from the observed flares, during the quiet state of the star, as a result of the general magnetic activity of the star. The power spectrum of these oscillations resamples that of the solar like oscillation spectra i.e the sunquake spectra. In particular the starquake spectra of EV Lac resamples that of a red subgiant.

Keywords: Flare stars-Discrete Fourier Transform analysis -Brownian Walk noise

1. Introduction

Brightness variations of EV Lac with a long period of 5 years has been reported by Mavridis and Avgoloupis (1986) and small period, small amplitude brightness variations of 4.378 days has been reported by Contadakis (1995). Similar behavior with periods 7.5 years and 3.5 days has been reported for BY Drac by Mavridis et al.(1995), while Contadakis (1996) reported a period of 3.829 days for this star. Both types of variation were explained on the base of star's flare activity and spottiness, in analogy of the solar flare activity (Alexeev and Gershberg 1997). High frequency optical oscillations during the quiescence phase of EV Lac with periods of 1 to 2 min, has been reported by Mavridis and Varvoglis (1993). High frequency, very small amplitude optical oscillations in dips with periods 1,95 and

4.25 min (Peres et al. 1993), 25 minutes before a flare on FF And, and oscillations with periods ranging between 4.38 and 18.37 min before the pre-flare dip on V 1045 Oph, has been reported by Ventura et al. (1995). The authors suggest that such brightness variations are common phenomena in active stars not connected with the flare phenomenon.

High-frequency small amplitude optical oscillations during a flare maximum of HII 2411 with a period of 14.4 sec has been reported by Rodono (1974) while high-frequency optical oscillations of amplitude 10% in U and 2.5% in B and period 14.4 seconds on a flare of EV Lac around the flare maximum phase has been reported by Zhilyaev et al.(2000). A multitude of high-frequency oscillations with amplitudes ranging between 1.4% and 2.6% and periods ranging between 6.9 sec and 20 sec around maximum phase and the subsequent stages of the flare evolution of a flare on EV Lac have been reported by Contadakis et al. (2004a). The resolution of the data was 1.2 sec. In a farther investigation on a flare of EV Lac with resoloution of 0.108s, Contadakis et al. (2006) reported high-frequency oscillations with periods ranging between 3.5 sec and 72 sec. It appears that the frequencies of the oscillations become higher and the amplitude decreases as the flare evolves. Similar behavior is reported by Contadakis et al. (2010) for the flare star AD Leo. In addition Contadakis et al. (2004b) analyzing a flare of 1992 on EV Lac with a data resolution of 12 sec, discover high-frequency oscillations on a flare of EV Lac with periods ranging between 30 sec and 125 sec. Finally, Zhilyaev et al. (2007) reported high-frequency oscillations just after the flare maximum with periods ranging between 4 sec and 6 sec. These results are consistent with the phenomenology of the evolution of a fast mode magneto-acoustic wave generated at the impulsive phase of the flare and traveling through the loop. The scientific team of the Stefanion Observatory, University of Thessaloniki, contributed to the research of high frequency optical oscillations on red dwarfs by participating in international programs for Multiwavelength observation of strong Flares of selected flare stars Howley et al. 2003, Zhilyaev et al. 2012. These joined researches shed plenty of light on the phenomenon of high frequency optical oscillations. Nevertheless a better understanding of the high-frequency oscillations, demand a unified analysis of the flare light-curve for a wider time window covering pre-flare, flare and post flare state and a broader band of frequencies. Thus in addition to the international campaign, the Stefanion Observatory group observe and analysis one color (B, or U) observations of different red dwarfs: EV Lac(Contadakis et al. 2004a,Contadakis et al. 2004b, Contadakis et al. 2006,Contadakis et al 2011d), AD Leo (Contadakis et al 2011a, Contadakis et al. 2011b),YZ CMin (Contadakis et al. 2010, Contadakis et al. 2012), UV Cet(Contadakis et al. 2011e), as well as the red giant (G8) V 390 Auri ,the flare activity of which was reported by Konstantinova-Antova et al.(2005, 2013), (Contadakis et al. 2011c, Contadakis et al. 2013and Contadakis 2013), at any stage of their activity (quiescence, weak flares, strong flares). In this paper we present the analysis of the quiet state observations of the Flare star AD Leo in order to realize if starquakes appear far apart from the observed flares, during the quiet state of the stars, as a result of the general magnetic activity of the star.

2. The Observations

The observations were curried out with the help of the 30-inch Cassegrain telescope of the Stefanion Observatory (φ=22^o 49’ 45’’, λ=37^o 45’ 09” and h=900m) which is equipped with a Johnson photometer. The digitized recording system has a recording resolution of 0.108s. This facility allows the reliable analysis of the observational data for a wide range of frequencies (4.63Hz to 4.63x10^{-3} Hz i.e. periods 0.216s to 216s) and permits the reliable spectral analysis of small part of the light-curve.

Table 1. The analyzed observations

Star	*Date*	*U.T.start*	*DT(U.T)*	σ_I	σ_{bw}
EV Lac	16/09/2004	19 19 58	04 04 26.6	0.0246	0.0154
		Useful part	02 01 00		

The Data consist of observations in the B color of the Johnson System of the star EV Lac in the quiescence state , during the years 2004. Table 1 give the general information of the observations and Figure 1 displays a sample of the analyzed light curve as an example. It should be noted that the light-curves are given in relative intensities $(I-I_o)/ I_o$ (I_o is the mean intensity of the quiet state star deflection)

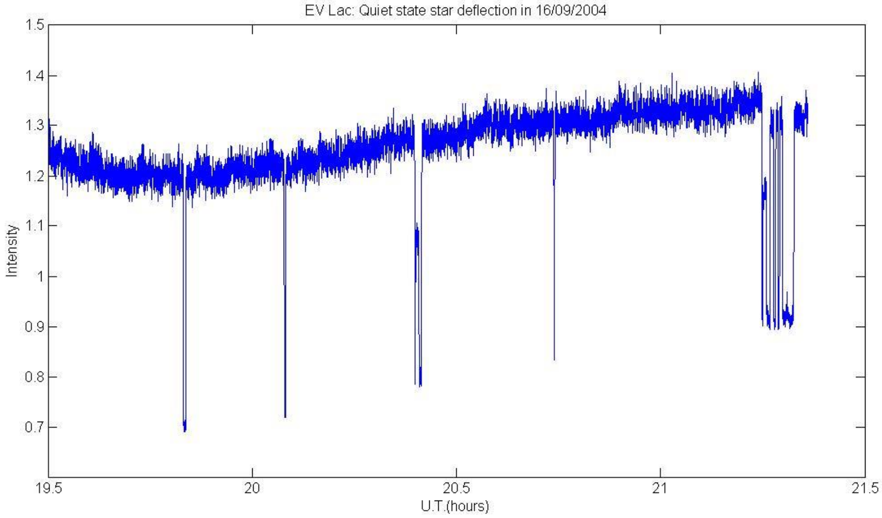

Figure 1. Quiet state star deflection of EV Lac on 16/09/ 2004

3. Analysis

In stellar photometry and particularly in the programs where unexpected stellar brightness variation are being under investigation, the standard procedure is the patrol monitoring of the star under investigation and the acquired data is a star brightness time series. The further analysis follows by analyzing these time series in order to discover any systematic, abrupt or periodical variation, which off course would have a particular physical meaning. The standard procedures for the analysis of the time series are: Discrete Fourier Transform analysis and Wavelet analysis. In this work we will use Discrete Fourier Transform analysis.

The data consist of a sample of relative intensities i.e. $(I-I_o)/I_o$, where I is the flare star intensity and I_o is the mean quiet star intensity. The extent, as well as the resolution, of the observational sample permit a reliable Discrete Fourier Transform analysis of sufficient light-curve parts for the determination of possible transient oscillations in the frequency domain and their approximate location in the time domain.

For the determination of the reliability of the results, key roll play the standard deviation of the photometry which is determined from the standard deviation of a certain part of the star deflection, as it is recorded by the recording facility at hand. This sample is considered, according to the observer's estimation (judgment) to reflect the noise of his photometric system and is clear from any real stellar brightness variation, which is assumed to be white noise. However the quiet star deflection is the sum of three components (a) the noisy stellar brightness assumed to be white noise (b) the inherent atmospheric noise which we assume to be random i.e. white noise and (c) the white noise of the recording system. If the memory of the recording system is short i.e. the system has large sampling intervals then the quiet star deflection is white noise. If the memory of the recording system is large i.e. the sampling interval is very short the quiet star deflection is Brownian Walk (Turkotte 1997). This is the case of the most stellar recording systems today.

Brownian Walk is an affine fractal and has a power low spectrum with b= -2 . (Contadakis et al. 2006, Contadakis et al. (2010a) and Contadakis et al.(2011). Our system has a sampling interval of 0.108 seconds which is very short.

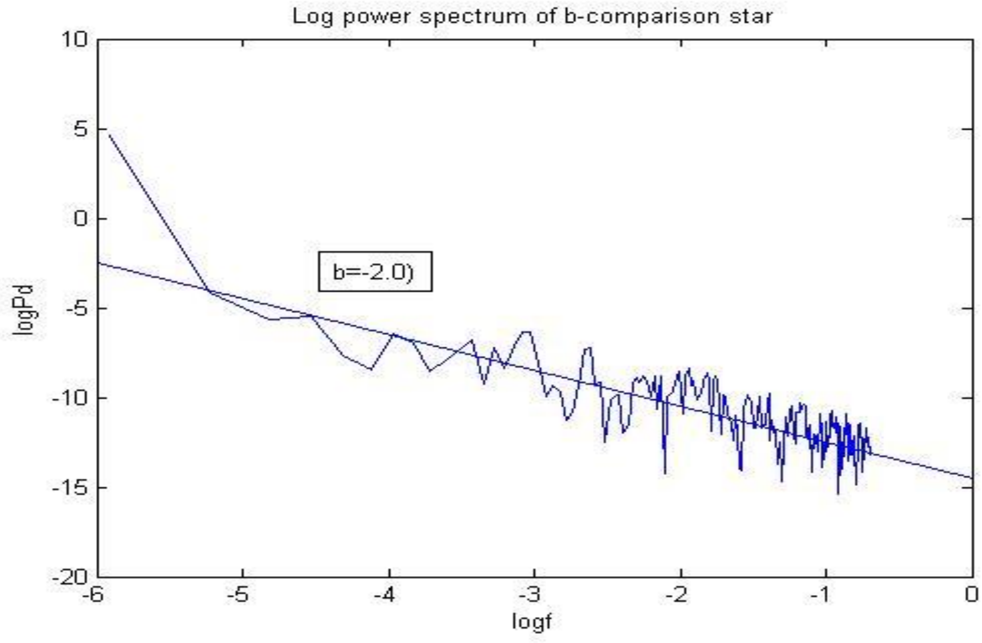

Figure 2. Logarithmic power spectrum of a not variable star.

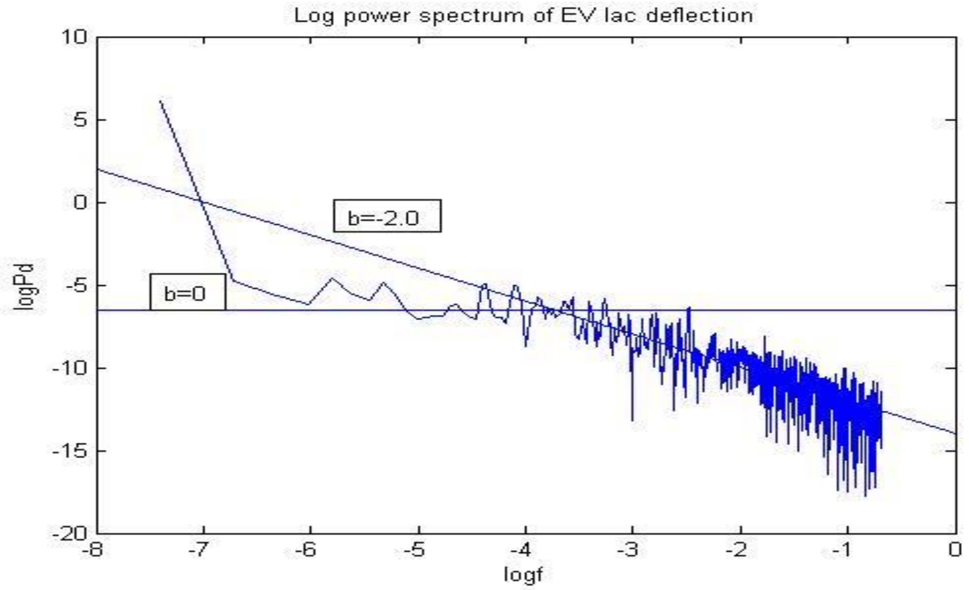

Figure 3. Logarithmic power spectrum at the quiescent state of the flare star EV Lac

Figure 2 displays the logarithmic power spectrum of a standard star (a not variable star which is used as a comparison star). It is apparent that the fluctuations of the standard star brightness are random (b=-2.0).
On the contrary from Figure 3, which displays the logarithmic power spectrum of the flare star EV Lac in the quiescent state, the random fluctuations of its deflection with frequencies higher than log(-3.8)= 0.0224 c/gap i.e. 0.2071Hz (period of 4.8277 second) show random behavior (b=-2), while the lower frequencies doesn't, indicating that they contain non random variations. In the particular case it became white noise with insignificant fluctuation superimposed by distinct picks. Shortly speaking, if the star deflection presents non random fluctuations the logarithmic power spectrum present a breaking point at the frequency where the non random fluctuations begin.
On the base of this property it is possible to separate the random noise of our data from the not random variations even from the signal of the active part of a star and further more to determine any non random deflection variation.
The standard deviation which is derived using the Brownian Walk part of the frequencies we call σ_{BW} and may be up to 30% smaller than the conventional one (the one which is determined by a part of the considered quiet star deflection). So the analysis comprises the following steps:

1. With the help of DFT-analysis we deduce the power spectra and the logarithmic power spectra of the flares and the quiet state star deflection. The logarithmic

power spectrum will enable us to separate the random part of the spectrum from the non random.

2. We isolate by filtering the random part of the spectrum and we estimate the standard deviation of the random noise σ_{BW}.
3. We identify the potential frequencies of star brightness oscillations from the power spectrum. To do this we use the Ho hypothesis test (see Contadakis et al. 2004a) in which σ_{BW} is used.
4. We filter out the identified frequencies from the star deflection.
5. We estimate the confidence level of those frequencies identifications comparing the amplitudes of the oscillations with the respective σ_{BW}.

4. Results

4.1 Transient Oscillations

The proposed analysis in this work permits an estimation of the random noise of the photometry at any part of the observation data, whether they concern flare deflection or not, and separate the real variations of the star light from the random noise. In addition permits the estimation of the confidence level of any identified transient frequency oscillation presented on the de-noised star deflection. The results of this analysis indicate that transient oscillations of frequencies do occur during the quiescent state. This is shown in Figure 4.

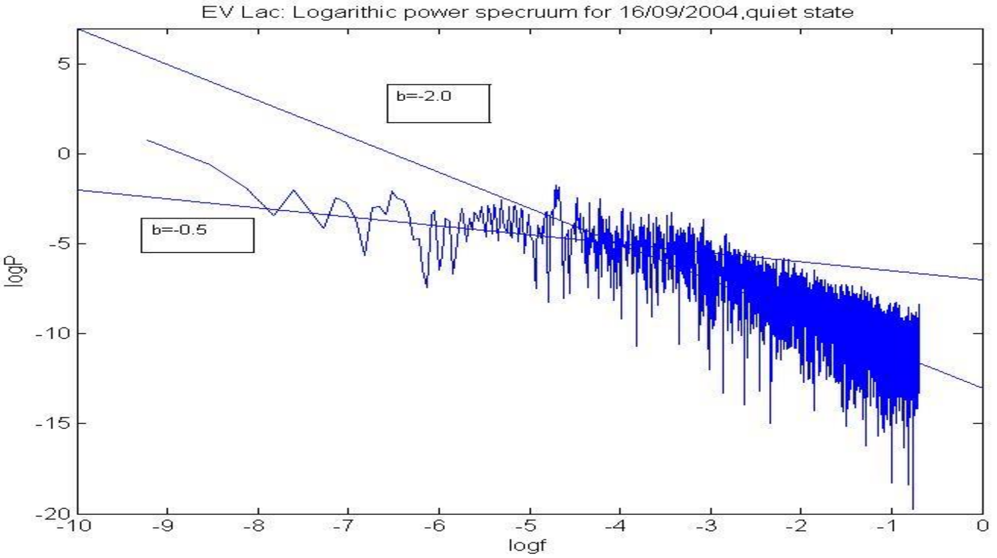

Figure 4. EV Lac. Logarithmic power spectrum of the quiet state star deflection on 16/09/2004. Limited log(frequency)=-4.0

From this figure it is apparent that the logarithm of the limited instrumental frequency below of which systematic variations on the quiet star deflections are being detected is -4.0. This means that the frequency below of which (or the period above of which) systematic oscillations on the quiet state star deflection are being detected are: f<0.1696 Hz, (period >5.8966sec).

Figures 5 display a de -noised specimen of the light curves of EV Lac which show the existence these transient oscillations. The horizontal lines indicate 1sigma of Brownian noise.

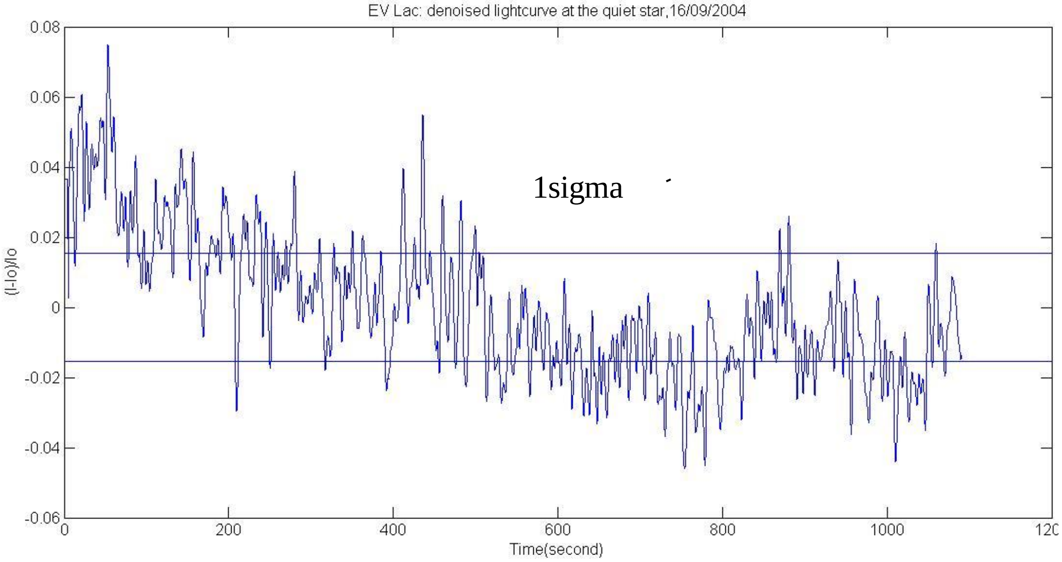

Figure 5. EV Lac: De noised light curve of the quiet state star deflection on 16/09 /2004. Transient oscillation of about 250sec superimposed by transient oscillations of about 20sec and so on.

The observed oscillations, which are identified with a confidence level lower than 30% (Probability of proper identification higher than 70%), are of the same frequencies range of the sunquakes which are high-degree, high-frequency p modes waves (standing acoustic waves). According to Kosovichev(2013) such oscillations can be excited by an impulsive localized force caused by the energy release in solar and stellar flares. The existence of starquakes may be a general characteristic of the active stars atmospheres and merit a specific research.

4.2 Starquakes

Although our observations were not oriented to astroseismic analysis, taking advantage to the optical observation of multi-periodic high frequency oscillations, we check the power spectrum of long segments of quiet state light curve from our routine monitoring patrol, in order to detect the existence of starquakes pattern. Figure 6 displays the power spectrum of a 2.016 hour long light curve segment of the quiet state light curve of the star.

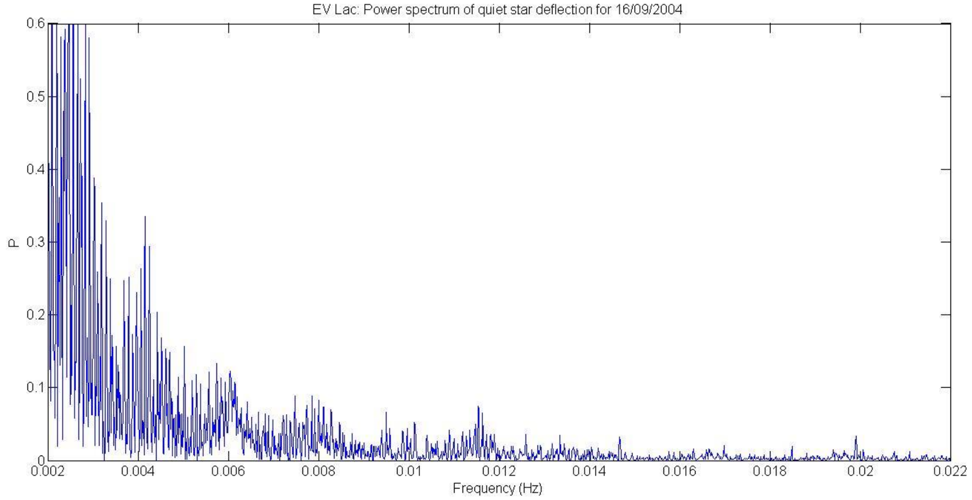

Figure 6. Power spectrum of a 2.016 hour long light curve segment of EV Lac

The frequency discrimination efficiency of the power spectrum is $\delta\boldsymbol{\nu}\approx\frac{\mathbf{1}}{\boldsymbol{T}}$. The monitoring specimen is T=2.016 hours thus $\delta\boldsymbol{\nu}\approx 138\mu\text{Hz}$.

The Lorengian shape of the power densities around 4000 μHz is similar to the solar starquake power spectrum at around 3000 μHz, which are p mode oscillations. Figure 7 focuses in this spectral area. In this spectrum we tentatively identify high order n, p mode radial oscillations of overtone order l= 0 and 1 in analogy to the solar and stellar spectrum. It is apparent that the highest power frequency is ν_{max} =4150μHz. The small frequency resolution does not allow the tentative identification of higher order overtone.

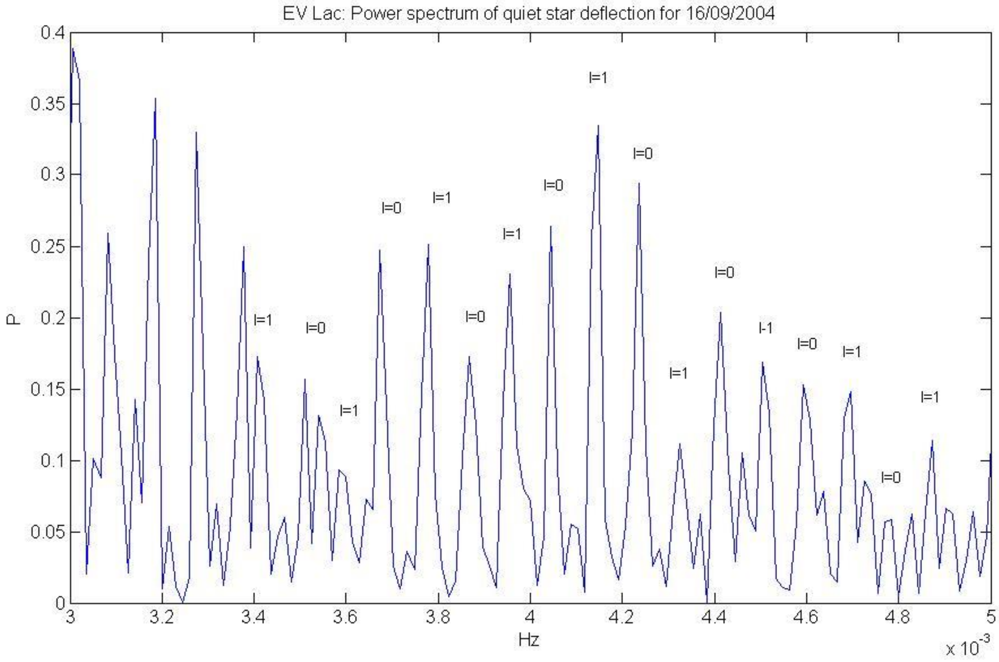

Figure 7. The power spectrum around the frequency of 4150 μHz. The tentative identification of p mode radial oscillations of order 0 and 1 is also shown.

In this power spectrum "avoided crossing" area around 3.6, 3.9, 4.3 and 4.8 mHz is apparent.

These avoided area maybe a result of the contamination of g or f mode oscillations with the p mode oscillations. Due to the marginal resolution of our observation we avoid any further speculations, leaving this task to future analyses on the base of proper, for asteroseismic analysis, observations with much higher S/N ratios. Never the less we proceed to a tentative estimation of the global asteroseismic properties, the frequency of maximum power ν_{max} ,and the mean large frequency difference $< \Delta\nu_{nl} >$.

Figure 8 displays the echelle diagram with frequency modulus 200μHz. From this diagram a large frequency difference of $< \Delta\nu_{nl} >$=180μHz is deduced while the avoided area are clearly indicated.

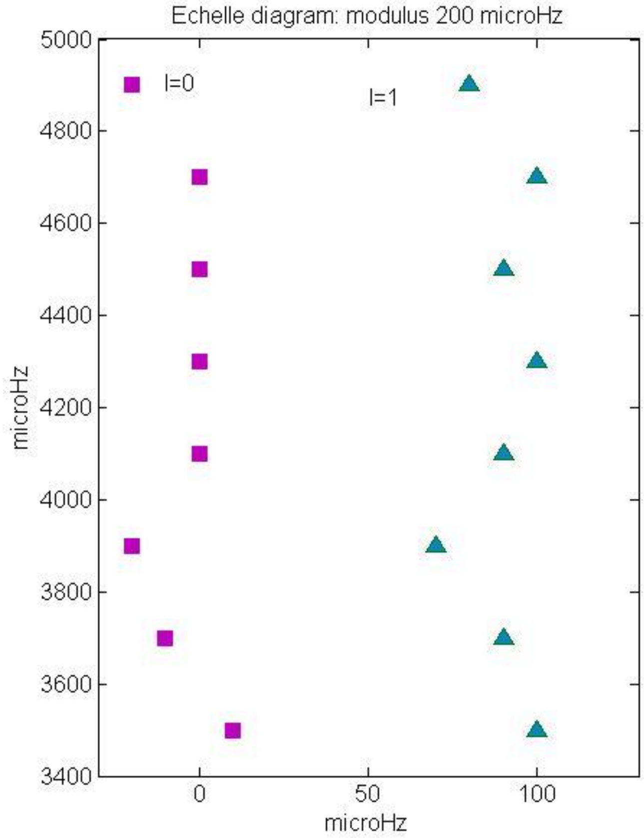

Figure 8. The Echelle diagram with frequency modulus 200 μHz

Our observations (figures 7 and 8) indicate that the star subject to p mode oscillations with maximum power frequency ν_{max} =4.150mHz and large frequency difference $< \Delta\nu_{nl} >$=180μHz, while the "avoided crossing" area may indicate a contamination of gravity (g or surface gravity f) mode oscillations with periods 278s ,256s, 233 and 208s and period spacing 22s,23s and 25s .

The moderate resolution do not allow identification of higher order modes for finer asteroseismic analysis. However , detailed asteroseismic investigations has shown that, if effective Temperature is known by some independent estimation, the main astrophysical parameters of the star can be estimated with sufficient, for statistic studies accuracy, by the asymptotic relations(Christensen- Dalgaard 2008, Chaplin and Miglio 2013). In this estimation we use $\nu_{max,o}$ =3.100mHz, $< \Delta\nu_{nl,o} >$ =135μHz and $T_{eff,o}$=5778, for the Sun (Chaplin and Miglio 2013) and T_{eff}=3400 for EV Lac (SIMBAD).

$$\frac{R}{R_o} \approx \left(\frac{\nu_{\max}}{\nu_{\max,o}} \right) \left(\frac{<\Delta\nu_{nl}>}{<\Delta\nu_{nl,o}>} \right)^{-2} \left(\frac{T_{eff}}{T_{eff,o}} \right)^{0.5} \quad (1)$$

$$\frac{M}{M_o} \approx \left(\frac{\nu_{\max}}{\nu_{\max,o}} \right)^{3} \left(\frac{<\Delta\nu_{nl}>}{<\Delta\nu_{nl,o}>} \right)^{-4} \left(\frac{T_{eff}}{T_{eff,o}} \right)^{1.5} \quad (2)$$

$$\frac{\rho}{\rho_o} \approx \left(\frac{<\Delta\nu_{nl}>}{<\Delta\nu_{nl,o}>} \right)^{2} \quad (3)$$

$$\frac{g}{g_o} \approx \left(\frac{\nu_{\max}}{\nu_{nl,o}} \right) \left(\frac{T_{eff}}{T_{eff,o}} \right)^{0.5} \quad (4)$$

Table 2. Main astrophysical parameter of EV Lac

	ν_{max} (mHz)	$\Delta\nu$ (mHz)	M/M_o	R/R_o	T_{eff}	g/g_o	ρ/ρ_o
EV Lac obs	4.150	0.180	0.332	0.569	3400	1.027	1.804
EV Lac lit			0.35	0.36	3400		
Sun	3.100	0.135			5778		

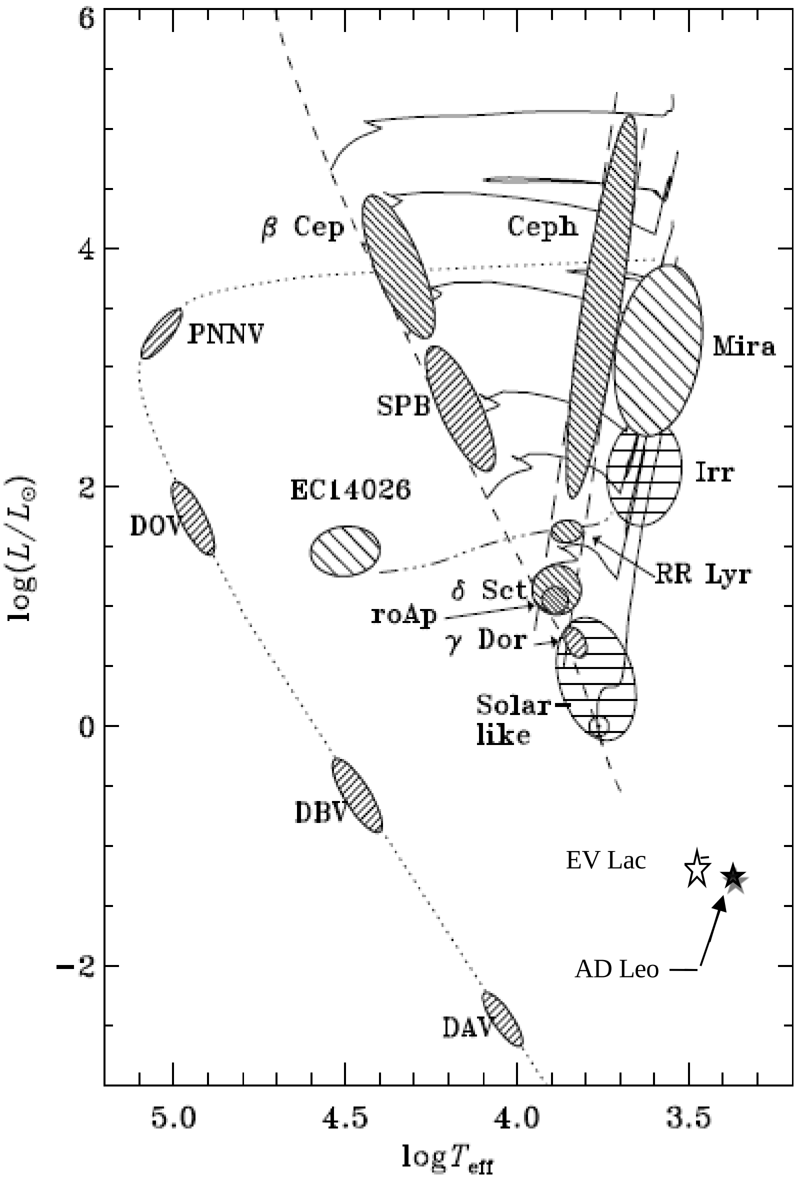

Figure 9. The place of EV Lac and AD Leo in the H-R diagram, according to the estimated astrophysical parameters.

Table 2 summarizes the main astrophysical parameter which were estimated in this analysis and Figure 9 displays the position of EV Lac in the H-R diagram according these estimates. In this diagram, quoting from Chaplin and Miglio 2013, the locus of the different types of starquake showing stars is marked.

Concluding Remarks

DFT-analysis and the use of the Brownian Walk noise notion enable us to estimate the proper random noise and to de-noise by filtering the observed light-curves. Thus we were able to detect possible weak transient optical oscillations and in addition to isolate them by proper band filtering. The confidence level of the identification is lower than 30% (Probability of proper identification higher than 70%).The results indicate that: (1) Transient high frequency oscillations occur during the quiet-star phase as it is happened during the flare phase too. (2) The Observed frequencies range between 0.008Hz (period 2min) and 0.3 Hz (period 3s) not rigorously bounded. The observed multiperiodic qscillations point to the existence of starquakes. Subsequent Fourier analysis of a 2.016hour specimen of the quiet state light curve revealed a solar like power spectrum of starquakes which are high-degree, high-frequency p modes waves (standing acoustic waves). The tentative identification of Solar type starquakes results to a very good asteroseismic estimation of the main astrophysical parameters of EV Lac. According to Kosovichev(2013) such oscillations can be excited by an impulsive localized force caused by the energy release in solar and stellar flares. The existence of starquakes may be a general characteristic of the active stars atmospheres and merit a specific research.

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